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Technical Notes

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Exploration of Outer Planets Using Tethers for Power and Propulsion

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Nomenclature

a	=	radius of circular orbit
$a(\max)$	=	radius at mechanical-energy maximum
a_{st}	=	radius of stationary orbit
B	=	planetary magnetic field
E_m	=	motional electric field
h_t	=	thickness of tape tether
I	=	current on tether
I_{av}	=	length-averaged tether current
L_t	=	tether length
M_{sc}	=	overall spacecraft mass
m_t	=	tether mass
N_{pl}	=	ionospheric electron density
R_J	=	radius of Jupiter
r	=	radial distance
r_{per}	=	radius at perijove
T	=	tether temperature
T_e	=	ionospheric electron temperature
v_{orb}	=	orbital velocity
v_{pl}	=	ionospheric plasma velocity
v_{rel}	=	relative velocity $v_{orb} - v_{pl}$
v_∞	=	hyperbolic excess velocity
w_t	=	width of tape tether
ε	=	tether emissivity
ε_{mech}	=	mechanical energy
ρ_{Al}	=	aluminum density
σ_{Al}	=	aluminum conductivity
σ_B	=	Stefan–Boltzmann constant

I. Introduction

AN editorial in *Aerospace America* in 2003 pointed at challenges facing missions to the outer planets.[1] Propellant mass required for capture by their planetary targets hampered the Galileo and Cassini missions, resulting in a protracted trip from Earth, scientific payload of a small percent in mass, and limited operations; radioisotope thermal generators substituting solar arrays prove to be weak power sources. The Jupiter Icy Moons Orbiter mission would overcome such limitations by using a nuclear reactor, directly for electrical power and indirectly for propulsion as power source of ion thrusters, which consumes 1/10th as much mass as rockets, thus enhancing mission maneuvering. In the alternative concept here presented, conductive tethers provide both power and propulsion, using a paradoxical feature of the thermodynamics of gravitation[2,3] to allow a tour of the Jovian system.

Use of tethers in Jupiter was briefly considered in early work by Penzo[4] and Hammond et al.[5] Penzo noticed that the Jovian gravity gradient is weak and, more important, that the thrust from current induced in tethers beyond certain stationary orbit would allow outward touring through a sequence of circular orbits. Hammond et al. discussed maximum power generated by tethers in circular orbits. The issue of electron collection by the tether was ignored in both analyses of tether current. Gabriel et al.[6] proposed light-ion emitters as anodes in a discussion of retrograde spacecraft capture, prograde energy tether assist, and inward and outward spiraling through circular orbits. Gallagher et al.[7] calculated spacecraft trajectories driven by electrodynamic tether forces, using some ad hoc mixture of sphere/bare-tether laws for electron collection. They considered retrograde capture followed by orbit circularization, and maneuvering in retrograde orbits, from equatorial to polar; they also discussed tether heating and possible tether severing by collision with micrometeoroids. Talley et al.[8] used spinning tethers and an electron-collection law for spherical anodes in discussing tether thrust and power generation at the giant Jovian moon orbits. In the present work, we devise a three-phase full tour of the Jovian system using a bare electrodynamic tether with a new prograde-orbit design that exploits the position of periapsis and apoapsis in elliptic orbits relative to the stationary orbit, allowing capture, navigation, and escape from Jupiter, with (almost) no need for propellant and power source. Bare-tether collection is carefully used, with results showing that no significant ohmic and thermal effects arise for realistic tether designs. A similar tour of Saturn and its moons might, in principle, be possible.

II. Thermodynamical Paradox in Gravitation

Thermodynamic equilibrium of an isolated system exhibiting macroscopic motion requires that mechanical energy reaches a minimum value (with entropy at a maximum) compatible with conserved momentum and angular momentum. Such a minimum, actually any extremum in mechanical energy, corresponds to rigid-body motion.[9] Different kinetic mechanisms dissipate mechanical energy in approaching rigid-body motion: Everywhere on Earth dry friction makes the relative motion of bodies stop. Air viscosity makes the atmosphere corotate with Earth. Tidal forces drive planet–moon systems to rotate as a single body; a spectacular example is the Pluto/Charon system, spins, and relative orbital revolution, all three having reached a common period of 6.39 days.

The simplest planet–satellite system has the orbit equatorial and circular and the satellite spin contributing negligibly to both total angular momentum and mechanical energy ε_{mech}, which are made of orbital and planet-spin contributions. Conservation of angular momentum makes ε_{mech} a function of only orbital radius a. In case of opposite angular momentum and orbital revolution (as with Earth's

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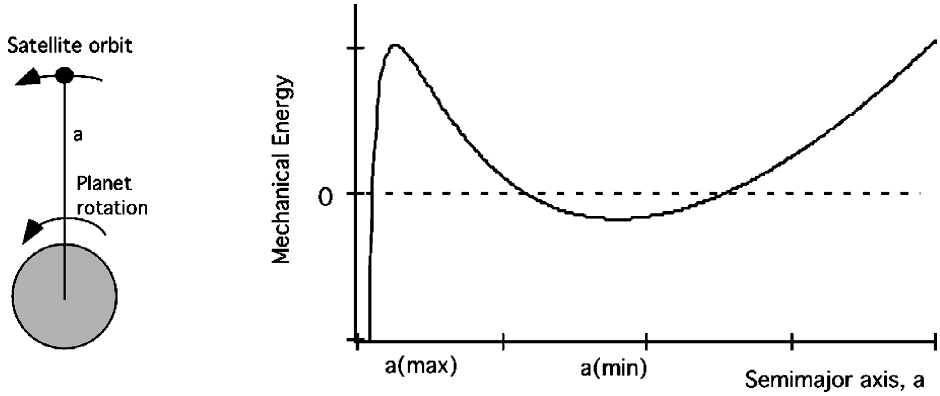

Fig. 1 Mechanical energy vs orbital radius for a satellite in an eastward, equatorial, circular orbit.

westward artificial satellites or Neptune's moon Triton), $\varepsilon_{\rm mech}$ decreases monotonically with a: Any dissipation would drive the satellite into the planet. On the other hand, for parallel angular momentum and orbital revolution, a graph of $\varepsilon_{\rm mech}$ vs a may exhibit two extrema[2]: a maximum and a minimum farther from the planet (Fig. 1). The observed Pluto/Charon orbit lies at the $\varepsilon_{\rm mech}$ minimum, at 16.5 Pluto's radius.

The $\varepsilon_{\rm mech}$ maximum is thermodynamically unstable in all cases: Any dissipation would take a satellite away from rigid-body motion at a(max) on either side of it. For the comparatively very light artificial satellites a(max) is the stationary radius $a_{\rm st}$ where all small satellites corotate with the planet. For Earth, $a_{\rm st}$ is 6.61 times its radius at the geostationary orbit. Satellites orbiting at $a < a_{\rm st}$ move faster than a corotating atmosphere, if present as in low Earth orbit, where they speed up while decaying from air friction in the so-called satellite paradox. A satellite at $a > a_{\rm st}$ moves slower than the atmosphere (if present), which would push it to higher and slower orbits.

III. Tether Drag and Thrust

Deploying a conductive tether from a spacecraft orbiting a planet with both ionosphere and magnetic field B introduces a new mechanism for dissipation, showing the thermodynamic features discussed earlier. In the highly conductive ionospheric plasma outside the tether (meters away from it, typically) the electric field is negligible in the frame moving with the local plasma velocity $v_{\rm pl}$. In a frame orbiting with the tether there is then a (motional) electric field,

$$\bar{E}_m = (\bar{v}_{\rm orb} - \bar{v}_{\rm pl}) \times \bar{B} \tag{1}$$

that may drive a current I inside the tether. The magnetic force on an insulated tether of length L_t electrically contacting the plasma through devices at both ends would be $L_t \bar{I} \times \bar{B}$, with $\bar{I} \cdot \bar{E}_m > 0$. One then has

$$(L_t \bar{I} \times \bar{B}) \cdot (\bar{v}_{\rm orb} - \bar{v}_{\rm pl}) = -L_t \bar{I} \times \bar{E}_m < 0 \tag{2}$$

showing power generated in the tether as net intake from ionosphere and tether motions. Whether $(L_t \bar{I} \times \bar{B}) \times \bar{v}_{\rm orb}$ is negative (drag) or positive (thrust) depends on $\bar{v}_{\rm orb}$ and $\bar{v}_{\rm orb} - \bar{v}_{\rm pl}$ having equal or opposite directions. For Earth, where $\bar{v}_{\rm pl}$ points eastward, drag acts in all westward orbits, whereas in eastward orbits the magnetic force changes direction with $\bar{v}_{\rm orb} - \bar{v}_{\rm pl}$ at $a_{\rm st}$: Drag acts below $a_{\rm st}$, thrust above $a_{\rm st}$.

Ion thrusters and rockets exert thrust at the cost of ejecting propellant, consumption being lower the higher the exhaust velocity, which is typically 3 km/s for rockets and 30 km/s for ion thrusters. The magnetic force on a tether requires no mass ejection, but devices (hollow cathodes) presently used to eject electrons at the cathodic end do eject some expellant. Expellant is consumed at a negligible rate, however. For values of the ratio current/(expellant) mass flow rate in state-of-the-art hollow cathodes, a field $B \sim 1$ G, and $L_t = 30$ km, a tether shows typical ratios of magnetic force to expellant mass flow rate of 10–30 × 10^3 km/s (Ref. 10).

The tether itself, left bare of insulation, establishes anodic contact by passively collecting electrons over a segment that comes out positive with respect to the plasma.[11] The collecting area of a bare tether is large because that segment is kilometers long, whereas collection is affected by neither space-charge shielding nor guiding of electrons by the ambient magnetic field if tether radius is less than about 1 Debye length and a fraction of the electron gyroradius. Those effects would greatly reduce collection by a large sphere of equal collecting area at the end of an insulated tether. A tape of width less than 4 Debye lengths would collect as much current as a round wire of equal area and would be much lighter, although its electric resistance would be greater.[12–14]

Going back to relative motion and thermodynamics, the Alfven engine concept[15] for interplanetary transportation was based on the interaction of a conductive (or superconducting) wire with the magnetized solar wind. Unlike our case of a tether orbiting a planet with a corotating magnetized ionosphere, however, Alfven's concept involves no maximum in mechanical energy. Under the Lorentz force on the induced current, Alfven's wire would just approach the local velocity of the solar wind.

IV. Tether Capture by Jupiter

Jupiter's plasmasphere reaches well beyond its stationary radius $a_{\rm st} \approx 2.24 R_J$, where $R_J \approx 71{,}400$ km is Jupiter's radius, its magnetosphere extending much farther out. For elliptical orbits, the region where current driven by the field $\bar{E}_m$ exerts drag on a tether is again, approximately, the drag sphere $r < a_{\rm st}$. For a tour of the Jovian system, the bare tether would have hollow cathodes at both ends, each end being allowed to act as anode (through bare-tether collection) or cathode. Current could be shut off at convenient points by switching off the hollow cathodes or plugging in a large resistance. Because both B and plasma density $N_{\rm pl}$ decrease rapidly away from Jupiter, tether drag or thrust would only operate near Jupiter, well within its plasmasphere. The tether could serve as its own power source by plugging in an electric load where convenient, the field $\bar{E}_m$ generating useful power with just some reduction on drag or thrust, as the case might be.

The Jovian tour starts with a critical capture operation (Fig. 2a). The spacecraft approaches Jupiter with the relative velocity of a minimum-energy transfer from Earth, $v_\infty \approx 6$ km/s. The perijove of this open orbit should lie inside the drag sphere, for example, at $r_{\rm per} = 1.5 R_J$. Limited propellant mass would be needed for trajectory correction maneuvers during the Earth–Jupiter trip and possibly for orbit trim maneuvers. The tether is deployed and a hollow cathode switched on before entering the drag sphere, to brake the spacecraft and make the orbit closed before leaving that sphere.

The voltage drop (tens of volts) at the active hollow cathode can be neglected in a first approximation. If the ohmic drop is neglected too, the bias voltage in a bare aluminum tape of width w_t, with the electric load for power generation unplugged, varies linearly from $E_m L_t$ at the anodic end to zero at the cathodic end, the length-averaged tether current being[11]

$$I_{\rm av} = \tfrac{2}{5} e N_{\rm pl} (2 w_t L_t / \pi) \sqrt{2 e E_m L_t / m_e} \tag{3}$$

To achieve capture by Jupiter over a path of estimated length $\pi r_{\rm per}$ inside the drag sphere, the drag must satisfy a condition

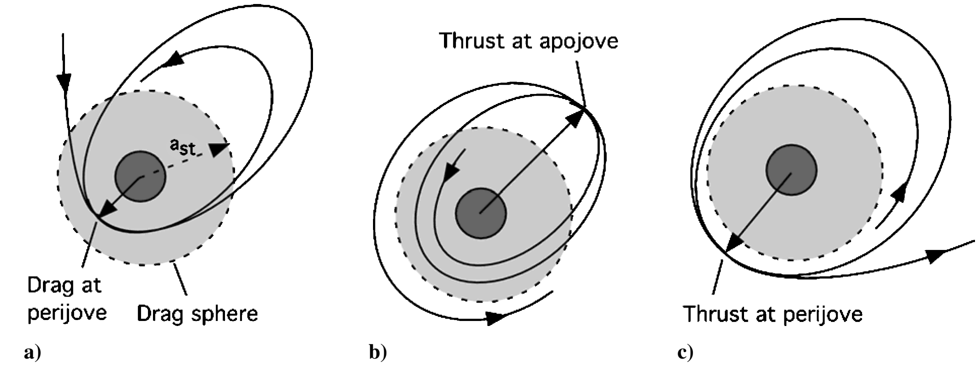

Fig. 2 Phases of a Jovian mission Using an electrodynamic tether: a) phase 1, capture and lowering apojove; b) phase 2, raising perijove; and c) phase 3, raising apojove and reaching escape velocity.

$L_t I_{av} B \pi r_{per} > \frac{1}{2} M_{sc} v_\infty^2$, which can be rewritten as

$$\frac{8 r_{per} m_e N_{pl}}{5 h_t} \frac{eB}{m_e} L_t \sqrt{\frac{2 e E_m L_t}{m_e}} > \frac{M_{sc}}{m_t} \rho_{Al} v_\infty^2 \tag{4}$$

the spacecraft mass M_{sc} includes the tether mass $m_t = \rho_{Al} L_t w_t h_t$, with ρ_{Al} and h_t being the tape density and thickness. With nominal values at $1.5 R_J$ about $N_{pl} = 10^3$ cm^{-3} ($T_e = 45$ eV), $B = 1.6$ g, $v_{rel} \equiv v_{orb} - v_{pl} = 30$ km/s $\rightarrow E_m = 4.8$ V/m Ref. 16, and taking $h_t = 0.1$ mm, $L_t = 40$ km, the preceding condition yields $m_t > 0.2 M_{sc}$.

A lower mass ratio m_t / M_{sc} could be achieved by placing the perijove closer to Jupiter, where the product $r N_{pl} B \sqrt{E_m}$ is greater, or by using thinner or longer tapes. The condition for ohmic effects to be negligible as just assumed (I_{av} small compared with the short-circuit current $\sigma_{Al} E_m w_t h_t$), which can be written as

$$\sigma_{Al} E_m^2 (2\pi r_{per} / v_{rel}) \gg (M_{sc}/m_t) \rho_{Al} v_\infty^2 \tag{5}$$

is satisfied by more than one order of magnitude.

Keeping tether temperature T within limits for a proper mechanical behavior results in another bound on mission and tether design parameters. The requirement that the power deposited by electrons at collection, $E_m L_t I_{av}$ (which equals the mechanical power for capture), be radiated away leads to the condition

$$(2\varepsilon / h_t) \sigma_B \left(T^4 - T_{bk}^4\right) (2\pi r_{per} / v_{rel}) = (M_{sc}/m_t) \rho_{Al} v_\infty^2 \tag{6}$$

where T_{bk} is a background temperature. Values $\varepsilon = 0.7$, $M_{sc} = 5 m_t$, and $T_{bk}^4 \ll 4 T^4$ yield a temperature $T = 400$ K that appears tolerable. A perijove farther from Jupiter or a thinner tape would reduce T or allow lower emissivity.

Tether width does not enter design considerations but does determine tether mass. Taking $w_t = 3$ cm, for example, yields $m_t \approx 324$ kg, $M_{sc} = 5 m_t \approx$ 1620 kg, and $I_{av} = 12.7$ A. Conditions for validity the of bare-tether current-collection law are well satisfied: Debye length and electron ambient gyroradius are about 1.6 m and 10 cm, respectively, and electron energy of motion relative to the tether, $\frac{1}{2} m_e v_{rel}^2$, is small compared with kT_e. Also, current collection by the tether is not affected by the (self-)magnetic field generated by the tether current itself: A characteristic sheath radius is of order of Debye length $\times \sqrt{e E_m L / k T_e} \sim 10^2$ m, whereas magnetic separatrix characterizing self-field effects[17,18] typically reaches a distance $I_{av} / 2\pi \varepsilon_0 c^2 B \sim 10^{-2}$ m that is about 10,000 times smaller.

V. Jovian Tour

The spacecraft must be hardened against radiation in the Jovian environment, as in the Galileo mission. As regards the threat of tether severing by collisions with micrometeoroids, a simple estimate[7] suggests that the probability of a 30-mm-wide tape surviving over a 10-year period in near-Jovian space would exceed 95%. Damage by Jovian ring particles, with typical size 10^{-4} tape width w_t, appears negligible. We note that the spacecraft only spends about 2 h ($\sim \pi r_{per} / v_{orb}$) inside the drag sphere during capture (Fig. 2a).

In the first phase, following capture, tether current is off all along the resulting elongated ellipse until reentering the drag sphere, when it is again switched on. This scheme is repeated in following passes: current on around perijove, inside the drag sphere, and off elsewhere. This reduces semimajor axis and eccentricity of the elliptic orbits, making the apojove reach in succesion each one of the big Jovian moons: Callisto at $11.8 a_{st}$, Ganymede at $6.7 a_{st}$, Europa at $4.2 a_{st}$, and Io at $2.6 a_{st}$.

A second phase (Fig. 2b) begins once magnetic drag has brought down the apojove close to the drag sphere. Now tether current is kept off around perijove and on around apojove, where thrust rather than drag applies (without resorting to a power supply but actually producing usable power, if needed). This increases the semiaxis but further reduces the eccentricity until the entire orbit is close to circular outside the drag sphere.

In the last phase (Fig. 2c), tether current is again on near perijove, where thrust rather than drag still applies, and off elsewhere, the evolution being the opposite of the first phase. Semi-major axis keeps increasing, eccentricity reaching near unity, until a final push makes the orbit open for a transfer back to Earth. Getting the spacecraft or some modules into orbit around Io or Europa would be easier at particular stages during the last phase.

Deployment of tens of kilometers long tethers has been performed succefully twice in the SEDS-I and SEDS-II mission in low Earth orbit (LEO).[19,20] Deployment here occurring before arrival at Jupiter, both gravity-gradient torque and Coriolis acceleration are low, hardly affecting deployment dynamics, unlike in the LEO case. A spring-ejection mechanism or a small gas thruster aligned with the tether can provide the initial separation velocity, later augmented by centrifugal forces when the system starts spinning, again before reaching Jupiter. Because of the low gravity gradient at $1.5 R_J$ and the comparatively large magnetic side force on the tether, a slow spin is a simple way to provide tether tension and dynamic stability.

A spin with a period of about 20 min when the tether is fully deployed will generate a tether tension that (depending on the system mass distribution) is from three to four times larger than the maximum magnetic force. This level of tension will keep tether lateral deflection small. The system can be spun by means of thrusters placed at the tether tips, requiring a negligible amount of propellant left over from the trip from Earth. With the direction of current always resulting in drag or thrust, as the case might be, the slow spin would allow each hollow cathode to act properly in phase during rotation to produce forces in the desired directions.

VI. Conclusions

We have shown how a space tether, as an alternative to nuclear reactors, could carry a spacecraft through a full tour of the Jovian system resorting to neither propellant nor power supply. The tether would be a conductive thin tape tens of kilometers long and a few centimeters wide, exploiting a paradoxical feature in the thermodynamics of gravitation to extract, throughout the tour, both electrical power and thrust or drag as required, from Jupiter's rotational motion. Tether heating is manageable even during the most demanding phases.

Acknowledgments

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