A 'FREE-LUNCH' TOUR OF THE JOVIAN SYSTEM

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Abstract

An ED-tether mission to Jupiter is presented. A bare tether carrying cathodic devices at both ends but no power supply, and using no propellant, could move 'freely' among Jupiter's 4 great moons. The tour scheme would have current naturally driven throughout by the motional electric field, the Lorentz force switching direction with current around a 'drag' radius of 160,00 kms, where the speed of the jovian ionosphere equals the speed of a spacecraft in circular orbit. With plasma density and magnetic field decreasing rapidly with distance from Jupiter, drag/thrust would only be operated in the inner plasmasphere, current being near shut off conveniently in orbit by disconnecting cathodes or plugging in a very large resistance; the tether could serve as its own power supply by plugging in an electric load where convenient, with just some reduction in thrust or drag. The periapsis of the spacecraft in a heliocentric transfer orbit from Earth would lie inside the drag sphere; with tether deployed and current on around periapsis, magnetic drag allows Jupiter to capture the spacecraft into an elliptic orbit of high eccentricity. Current would be on at succesive perijove passes and off elsewhere, reducing the eccentricity by lowering the apoapsis progressively to allow visits of the giant moons. In a second phase, current is on around apoapsis outside the drag sphere, rising the periapsis until the full orbit lies outside that sphere. In a third phase, current is on at periapsis, increasing the eccentricity until a last push makes the orbit hyperbolic to escape Jupiter. Dynamical issues such as low gravity-gradient at Jupiter and tether orientation in elliptic orbits of high eccentricity are discussed.

Introduction

The present work is motivated by the challenges facing the exploration of the outer planets. A recent editorial in *Aerospace America* pointed at the basic difficulties [1]. Solar Power is insufficient at Jupiter and beyond. Radioisotope Generators are weak power sources (and they are heavy, and a source of heat and a danger to the electronics).

Propellant mass is the main issue, however. Just allowing capture by their planetary targets has placed a heavy toll on both the Galileo and Cassini missions, reducing scientific payload to a few percent of the respective 3-ton and 6-ton masses, and limiting mission lifetime. Getting a spacecraft into low, near-circular orbit appears beyond the reach of gravity assists.

The *Aerospace America* editorial advocated NASA's *Project Prometheus* on the use of nuclear reactors for outer-planet missions. Nuclear reactors would be directly used for electric power, and indirectly used for propulsion, as power source of electrical thrusters. The

1-order of magnitude gain in specific impulse as compared to chemical propulsion would greatly extend mission lifetime.

In the present work, electrodynamic (ED) tethers are discussed as providing both power and propulsion in an extremely efficient way for outer-planet missions. A seemingly paradoxical tour of the Jovian system is proposed. Some characteristic features of the thermodynamics of gravitation, which underlies that tour concept [2] - [3], and the relevant basics of ED-tethers, are first recalled.

Thermodynamics and Gravitation

Consider an isolated system conserving momentum, angular momentum, and energy, but exhibiting macroscopic motion. Thermodynamic equilibrium requires that entropy and thus internal energy be maximum. To conserve total energy, macroscopic energy (which need not be purely kinetic) must reach a minimum value compatible with the overall magnitudes conserved. Such minimum corresponds to rigid-body motion.

Different kinetic mechanisms are responsible for the dissipation of macroscopic energy in the approach to that equilibrium. In the trivial case of two blocks sliding on each other upon a frictionless floor, dry friction is involved in getting the blocks to finally move jointly as a rigid body. Air drag is determinant in making atmospheres corotate with their planets. Tidal forces are determinant in the equilibrium of planet-moon systems.

In a planet-moon system, both moon and planet rotations and the relative orbital revolution contribute to the angular momentum, H_0. The macroscopic energy ε_{Macro} involves, in addition, the gravitational interaction. In the simplest case, all three angular velocities for the two spins and the orbital revolution, ω_m, ω_p, and Ω_{orb}, are parallel, and the orbit is equatorial and circular. The condition $H_0 = const$ allows writing the macroscopic energy as $\varepsilon_{Macro}(\omega_p, \Omega_{orb})$, with semiaxis (radius) a related to Ω_{orb} by Kepler's law.

The condition for minimum $\varepsilon_{Macro}(\omega_p, \Omega_{orb})$ yields two relations leading to rigid-body motion,

$$\omega_m = \omega_p = \Omega_{orb}.$$

A spectacular example of this type of equilibrium is the *Pluto*/*Charon* system: the spins of both planet and moon, and the relative orbital revolution, all three have periods of 6.39 days... The *Earth*/*Moon* system, not quite fitting the simple-case conditions, has only achieved yet the locking of *Moon*'s spin with its orbital revolution.

Whenever a moon, say a satellite in general, makes a negligible contribution to both H_0 and ε_{Macro}, the condition $H_0 = const$ allows writing $\varepsilon_{Macro}(\Omega_{orb})$, or $\varepsilon_{Macro}(a)$. If Ω_{orb} is opposite H_0 (case of *Earth*'s westward satellites, and *Neptune*'s moon *Triton*), then $\varepsilon_{Macro}(a)$ decreases monotonically with decreasing a; any dissipation will make the satellite fall into the planet. If, however, Ω_{orb} and H_0 have the same direction (as with *Earth*'s eastward satellites) <u>and</u> $H_0 > 4 \times [(GM_p)^2 M_m^3 I_p/27]^{1/4}$, then a graph ε_{Macro} versus a exhibits extrema at two distances, where $\Omega_{orb} = \omega_p$: a maximum, and a minimum farther from the planet.

The (relative) minimum is a metastable thermodynamical equilibrium (it corresponds to a *relative* maximum of entropy), while <u>the maximum is thermodynamically unstable under</u>

dissipation; this is a case of rigid-body motion being unstable. For man-made satellites a_{max} is the geostationary radius, $r_{gE} \approx 42{,}200$ km (with dissipation times unphysically large, however). For $a < a_{max}$ we have $\Omega_{orb} > \omega_p$, as in the case of satellites at LEO altitudes, which decay from air friction with the slow corotating atmosphere.

ED Tethers

Deploying a conductive tether orbiting a planet that has ionosphere and magnetic field introduces a new kinetic mechanism for dissipation. Consider the Lorentz transformation of any electric and magnetic fields $\overline{E}$ and $\overline{B}$ in going from a frame moving with the local ionospheric plasma to a frame orbiting with the tether, the relative velocity being non-relativistic,

$$\overline{E}\,(tether\ \ frame) \;=\; \overline{E}\,(plasma\ \ frame) \;+\; \overline{E}_m\,. \tag{1}$$

Here $\overline{E}_m$ is the so-called induced electric field,

$$\overline{E}_m \;\equiv\; (\overline{v}_{orb} \,-\, \overline{v}_{pl}) \,\wedge\, \overline{B}\,, \tag{2}$$

and $\overline{B}$ is the same in both frames.

Far from the tether (meters away, typically) the electric field in the highly conductive plasma is zero (or just negligible when compared with $\overline{E}_m$), yielding

$$\overline{E}\,(tether\ \ frame) \;=\; \overline{E}_m \qquad\qquad \text{(outside).} \tag{3}$$

Equation (1) also holds inside the tether, where it provides no useful information however. On the other hand, if current flows along the tether, Ohm's law holds inside, in the tether's own frame,

$$\overline{E}\,(tether\ \ frame) \;=\; \overline{J}_e\,/\,\sigma_{cond} \qquad\qquad \text{(inside).} \tag{4}$$

For the simplest circular, equatorial orbit of Sec.2, and a centered, no-tilt dipole field, $\overline{B}$ is horizontal and lies in the meridian plane, and $\overline{E}$ is parallel to the tether, assumed vertical (a non-parallel component will in general produce a negligible potential difference accross the thin cross section of the tether). For an insulated tether making electric contact with the plasma through devices at both ends, the fields given by Eqs. (3) and (4) would be equal in the limit case of vanishing contact impedances. In general, $\overline{E}_m$ and $\overline{J}_e$ will have the same direction. The Lorentz force on the current *I* along the tether will be

$$L_t\,\overline{I} \wedge \overline{B} \qquad\qquad (\overline{I} \bullet \overline{E}_m > 0)$$

We then have

$$(L_t\,\overline{I} \wedge \overline{B}) \,\bullet\, (\overline{v}_{orb} \,-\, \overline{v}_{pl}) \;=\; -\,L_t\,\overline{I} \bullet \overline{E}_m \;<\; 0\,,$$

the negative sign meaning that electrical power is produced in the tether.

Whether $(L_t\,\overline{I} \wedge \overline{B}) \bullet \overline{v}_{orb}$ is positive (implying thrust) or negative (implying drag) depends on $\overline{v}_{orb}$ being opposite or having the same direction of the relative velocity

$\bar{v}_{orb} - \bar{v}_{pl}$. Going back to the case of Earth satellites, with $\bar{v}_{pl}$ pointing eastward, one can readily check that drag applies to westward orbits always, whereas, for eastward orbits, there is thrust beyond the geostationary radius r_{gE} where $\bar{v}_{orb} - \bar{v}_{pl}$ changes direction, and drag for $a < r_{gE}$. Note that these results from an analysis of the dissipative mechanism introduced by the tether are in agreement with the purely thermodynamic analysis of Sec.2, which applies to any kinetic mechanism.

(Note also that the example of a centered, no-tilt dipole magnetic field - Saturn's field being quite close to that limit model - shows clearly that tether thrust or drag does not result from *the magnetic field* moving faster or slower than the tether, an erroneous statement seen frequently.)

The Lorentz force, whether thrust or drag, is not related to high-velocity ejection of propellant. A tether therefore imposes no toll on a spacecraft, ensuing from a requirement of propellant mass. Devices (Hollow Cathodes) used at present with EDTs do eject some expellant with the electron current ejected at the cathodic end, but, typically, the (Xenon) mass expelled is about 1000 times smaller than the propellant mass consumed by an equal-thrust rocket. For the rocket one has

$$\frac{Thrust}{\dot{m}_{prop}} = v_{exh} \approx 3\,\frac{km}{s}.$$

An Ion thruster has an exhaust velocity ($specific\ \ impulse \times aceleration\ \ of\ \ gravity$) about 10 times greater, thus consuming only 10 times less mass for given thrust.

In the case of a tether, one can define an equivalent 'exhaust' velocity based on the ratio *current*-to-*expellant mass flow rate* at the Hollow Cathode, which has the same dimension of the *charge*-to-*mass* ratio of a particle (for state-of-the-art Hollow Cathodes, this is the ratio of an ion of atomic number 6-10), and leads to a 'gyrofrequency' when multiplied by the magnetic field [4]. One finds

$$\frac{Lorentz\ \ force}{\dot{m}_{hc}} \approx L_t \times \frac{I_{hc}}{\dot{m}_{hc}} B \approx 7000\frac{km}{s},$$

$$\left(B \approx 0.3\ gauss, \qquad \frac{I_{hc}}{\dot{m}_{hc}} \times B \approx 350\frac{1}{s}, \qquad L_t \approx 20\,km.\right)$$

At the anodic end, passive collection is used. The tether itself, left bare of insulation, collects electrons over a segment coming out positively. The collecting area is large because the anodic segment is kilometers long. For some operating regimes that segment comes out longer the lower the density of ionospheric electrons: bare-tether current can self-adapt to electron-density drops occurring in orbit [5].

As opposite collection by a large sphere, collection by a typically thin (radius up to 1 Debye length) bare tether is not reduced by space-charge shielding, because the two-dimensional electric potential it sets up dies off gradually with distance. Also, the planetary magnetic field that guides electrons along thin helices, may greatly reduce collection by a large sphere but hardly affect collection by a thin tether. Note that a tape would collect as much current as a round wire with equal perimeter of cross section (and would be much lighter), if its width does not exceed 4 Debye lengths [6].

A 'Free-Lunch' Tour of the Jovian System

The equivalent of the geostationary radius for Jupiter, r_{gJ}, is about 2.24 R_J, where $R_J \approx$ 71,400 km is Jupiter's radius. This stationary distance lies well within Jupiter's plasmasphere, its complex magnetosphere extending much farther out. (For Earth, one has $r_{gE} \approx 6.6\ R_E$, plasma density and magnetic field being already extremely weak at the geostationary distance.) We may talk of a 'drag sphere', defined by condition $r < r_{gJ}$. As seen in Secs.2 and 3, the current 'naturally' driven along a tether in circular orbit by the induced electric field will result in drag for $a < r_{gJ}$ and thrust for $a > r_{gJ}$. This also applies approximately at $r < r_{gJ}$ and $r > r_{gJ}$, respectively, for elliptical orbits.

A paradoxical use of an ED bare tether for a tour of the Jovian system would follow this conceptual scheme: The tether would have Hollow Cathodes at both ends, each end allowed acting as cathodic or anodic. Current could be practically shut off at convenient points, by switching off the Hollow Cathodes/plugging in a very large resistance; since both plasma density and magnetic field decrease rapidly with increasing distance from Jupiter, tether drag or thrust would only operate near Jupiter, well within its plasmasphere. The tether could be used as its own power source by plugging in an electric load, again where convenient, the induced electric field generating useful power (to be stored) with just some reduction on drag or thrust as the case might be.

The tour would involve a capture phase and three additional phases, the capture phase being critical: the tether orbit, once closed, can be made to evolve dramatically by repeatedly applying the Lorentz force, even if weak. The spacecraft is assumed to approach Jupiter with the relative velocity resulting from a minimum-energy transfer from Earth, about 6 kilometers per second. The periapsis of this open (relative to Jupiter) orbit would lie inside the drag sphere, say at 1.5 R_J. Limited propellant mass would be needed for any required Trajectory Correction Maneuvers during the Earth-Jupiter trip, when the Lorentz force is not available.

The tether is deployed when entering the 'drag sphere', Jupiter's magnetic field braking the spacecraft continuously to barely close the orbit before leaving that sphere. At 1.5 R_J the velocity to escape Jupiter is about 48.5 km/s, the minimum Δv required being only 0.33 km/s. Taking Δv = 0.67 km/s leads to a highly elongated ellipse of 50-days period, and an apoapsis at 107.9 R_J. (Capture into a ellipse of greater period would be, of course, less requiring. Galileo had a first perijove at 4 R_J and was captured into a closed orbit of 198-days period, the Δv applied being only slightly greater than the minimum Δv required.)

Using electron density $N_\infty = 10^3 cm^{-3}$, B = 1.6 gauss, E_m = 4.8 V/m at 1.5 R_J and taking a total spacecraft mass $M_{S/C} = \alpha_t$ times the mass of the tether (an *Al* tape of width w_t and thickness h_t) we find that ohmic effects are negligible. A condition on the average Lorentz force to produce Δv = 0.67 km/s, setting h_t = 0.05 mm, α_t = 4 requires a tether length $L_t \approx$ 34.8 km. Taking w_t = 6 cm leads to $M_{S/C} \approx$ 1124 kg (including tether mass ≈ 281 kg).

A simple estimate of heating effects shows that it is possible to keep the tape at a working temperature. On the other hand, because of the low gravity gradient at 1.5 R_J, and the large magnetic force the tether may support, some scheme to provide tension and dynamic stability is required. One way is setting the tether into a slow spin of period about 30 minutes (before the orbit is closed and orbital/attitude coupling itself could get the tether spining). This can be done with thrusters at the tether tips, requiring about 10 kg of propellant left over from the trip from Earth. With the direction of current always resulting in drag, that slow spin could allow each Hollow Cathode act as needed at the proper phase in rotation.

In a second phase, tether current will be off all along the elongated ellipse of capture until the spacecraft reenters the drag sphere, when again it is switched on. A second Δv = 0.67 km/s velocity reduction would lead to a 35 R_J apoapsis. This scheme is repeated in following passes: current on around periapsis, inside the drag sphere, and off elsewhere, to produce drag. This reduces the semi-major axis of the elliptic orbit, progressively making the apoapsis reach in succesion each one of the 4 big moons of Jupiter: *Callisto* at 11.8r_{gJ}, *Ganymedes* at 6.7r_{gJ}, *Europa* at 4.2r_{gJ}, and *Io* at 2.6r_{gJ}.

The third phase begins once magnetic drag brings down the apoapsis close to the drag sphere. Now tether current is kept on around apoapsis, where thrust rather than drag applies, and off around periapsis. This reduces the eccentricity, until the entire orbit lies outside the drag sphere and is not far from a circle.

In a last phase tether current is again on during periapsis, where thrust, rather than drag, still applies and off elsewhere, the evolution being the opposite of the second phase. Semi-major axis keeps increasing, reaching eccentricities very near unity, until a final push makes the orbit open for a transfer back to Earth.

Conclusions

ED bare tethers may represent a powerful alternative to the use of nuclear reactors for outer-planet missions, although careful tradeoff analyses are required to go beyond the conceptual scheme and simple calculations presented here.

References

1. E. Camhi and J. Grey, Aerospace America **41**, Editorial (2003).

2. J.R. Sanmartin, Eur. J. Phys. **16**, 8 (1995).

3. D.P. Sheehan, J. Glick, T. Duncan, J. A. Langton, M. J. Gagliardi, and R. Tobe, Found. Phys. **32**, 441 (2002).

4. J.R. Sanmartin, R. D. Estes, and E. C. Lorenzini, in Space Technology and Applications International Forum 2001 (ed. M.S.El-Genk, Am. Ins. Phys., New York, 2002), pp. 479-487.

5. R.D. Estes, E. C. Lorenzini, J. R. Sanmartin, J. Pelaez, M. Martinez-Sanchez, C. L. Jonhson, and I. E. Vas, J. Space. Rockets **37**, 205 (2000).

6. J.R. Sanmartin, in Space Environment: Prevention of Risks Related to Spacecraft Charging (eds. J-P. Catani and M.Romero, CNES/ONERA, Toulouse, 2002), pp.515-533.