OVERALL REVIEW OF THIN-TAPE BARE TETHERS OPERATION AS JUST THERMODYNAMIC PROCESS

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EXTENDED ABSTRACT

This work will be a mixture involving all three types of contributions solicited by the 14th SCTC:

A) Retrospective Review of 'forgotten' old work
B) Review of recent advance
C) New research

As regards **A),** the basic physics underlying electrodynamic tether operation is reviewed; also how it all started and the respective roles of *Drell et al.* [1], who introduced the confusing name of *Alfven* Propulsion; *R. D. Moore*'s fundamental 1966 work [2]; the 1972 acknowledgment of Moore's work precedence by six years, by *H. Alfven* [3]; and the 1984 historical Review by von Tiesenhausen [4].

A) further involves recalling *rigid-body* motion as definite property of thermodynamic equilibrium of macroscopic systems, a consequence of maximum entropy requiring maximum internal energy and minimum macroscopic energy ε, this being a characteristic of rigid-body motion. Also how well known introductory *treaties* like the Feynman Lectures, and advanced *treaties* like the *Sommerfeld Lectures* fully ignore that thermodynamic *principle.*

The approach to equilibrium may involve different dissipative physics: dry friction, viscosity, tidal forces... The case of tethers involves *Relativity* physics. In the frame of a tether moving through a magnetized ambient plasma, there is a *motional* electric field $\boldsymbol{E_m}$ in the plasma**,** proportional to both relative velocity and ambient magnetic field $\boldsymbol{B_0}$. The motional field may drive a current in the wire, the Lorentz force on that current thus involving the field $\boldsymbol{B_0}$ a second time. This makes the unidirectional, thermodynamic character of the Lorentz force, a drag, manifest.

Drell et al assumed that the main impedance in the tether current circuit closure through the ambient plasma was Alfven-waves radiation impedance. *Moore* considered that the impedance for ambient plasma/wire contact was dominant, requiring active contactors, both anodic and cathodic. He also realized that a long wire would be needed for a large motional electromotive force, the gravity gradient possibly helping to keep it vertical.

Moore took the tether concept from *Low Eearth Orbit* to the Solar Wind, an application that Alfven considered later. There is a basic difference between tethers orbiting planets and in solar-wind use. For systems large enough that gravitational energy need be accounted for macroscopic energy *ε*, *rigid-body* motion may occur away from thermodynamic equilibrium.

The consequence is one of the thermodynamic paradoxes of gravitation (a well-known one being the *Jeans* instability): *Rigid-body* motion may then correspond to two opposite types of *extrema*. It may indeed correspond to *ε* minimum (entropy maximum, at thermodynamic equilibrium), case of *Charon* orbiting *Pluto*, but also to *ε* maximum (entropy minimum, far away from thermodynamic equilibrium), case of the *geostationary* orbit. This is why satellites re-enter, escaping from *rigid-body* co-rotation with Earth, at geostationary.

There is, anyway, a basic difficulty in using the *motional* Lorentz drag in the Solar Wind, that being its extremely low values of both ambient plasma density and magnetic field. This has given rise to the alternative electric solar-sail concept, using an array of wires biased by solar power to deflect Solar Wind ions, hence generating drag/thrust through Coulomb, rather than Lorentz, forces [5]. Note that this scheme does require use of an independent power source.

Paradigmatic missions which are just thermodynamics are found both, **B**) at *Earth*, and **C**) at *Jupiter* and, in general, at the *Outer Giant* planets.

B) As regards review of recent advance, de-orbiting satellites at end of life, so as to prevent generation of new space debris, is a definite mission exhibiting the thermodynamic character of electrodynamic tethers. Space debris remain a constant menace to operative satellites in Low Earth Orbit. A basic analysis on the *tape* geometry of tethers as de-orbit systems to be used just at end of mission follows work on overall development of tether systems, under a Project, *BETs*, supported by the *European Commission* from November 2010 to February 2014 [6].

Thorough, recently published results show how using thin-tape bare tethers allows design that satisfies all 4 requirements on tethers as systems for end-of-mission de-orbiting of spacecraft or just *derelict* spacecraft, at all inclinations: *i*) Small tether-to-SC mass ratio m_t/M_S, *ii*) low probability N_f of tether cut by small debris, and short de-orbit time t_f, such as leading to *iii*) low *Area* × *time* product $d_{SC}^2 \times t_f$ characterizing the probability of catastrophic collision with another big S/C, and *iv*) reasonably low *Area-time* product $d_{SC} \times L \times t_f$ that characterizes the minor accident of a big SC impacting the tether (size $d_{SC} \sim 2 - 3$ m, L tether length).

The design scheme involves two figures of merit, the product $\mathbf{\Pi}$ of probability N_f of a cut by debris and mass ratio m_t/M_S, and a product $\boldsymbol{\tau}$ involving de-orbit time t_f and mass ratio m_t/M_S. The analysis explicitly shows $\mathbf{\Pi}$ as a functional of orbital parameters and satellite mass, and tether geometry (width *w*, thickness *h*, and ratio of length L to $h^{2/3}$), which is derived by combining a fatal-impact rate model introduced in [7] and a simple satellite dynamical equation, which assumes a slow de-orbit evolution due to Lorentz drag, as sequence of near-circular orbits. Product $\boldsymbol{\tau}$ follows directly from the dynamical equation and depends on geometry through just $L/h^{2/3}$.

Universal tape-tether design, involving selection of all three, length, width, and thickness, is discussed for particular missions: initial orbit of 720 km altitude and 63° and 92° inclinations, and 3 disparate M_S values, 37.5, 375, and 3750 kg, design proving scalable. Performance is then gauged, as indicated above, by requiring very low N_f and mass ratio m_t / M_S, and short de-orbit time t_f and low $t_f L$. At mid-inclination and 2% m_t/M_S mass-ratio, de-orbit time takes about 2 weeks and N_f is a small fraction of 1%, with tape dimensions ranging from 2.8 to 8.6 km, 1 to 6 cm, and 10 to 54 μm. Performance drop from middle to high inclination proved moderate: if allowing for twice as large m_t/M_S, increases are reduced to a factor of 4 in t_f and a slight one in N_f. Multi-ton S/C are more requiring because efficient *orbital-motion-limited* collection restricts tape-width values, resulting in tape length (slightly) increasing along with thickness [8].

Although electrical power is involved, the tether system, in addition to allow low-mass scalable design, is a passive system, needing neither propellant nor auxiliary power and arising from just thermodynamics and thus being reliable as air drag. New low *Work Function* materials might actually do away with use of the *Hollow Cathode* plasma contactors; the bare-tether tape geometry would also do away with the need of a multi-line tether to resist the small debris menace. Tape tethers de-orbits fast, about two weeks for initial altitudes 700-750 km at mid-inclinations and two months at high inclination, as discussed, and estimates show de-orbit time keeping well as fraction of year for altitudes around 1000 km, high inclination conditions..

As regards **C**), preliminary work just presented at the recent *EPSC*-2015 at Nantes, and work submitted for publication, re-considers studies on tether missions to the *Jovian* system: Use of tens-of-kilometre long tapes, which receives attracted electrons very energetic that Lorentz drag might require because of the low ambient plasma density, may result in electrons (intended to be collected) actually reaching the tape with *range* (penetration length) exceeding tape thickness.

Design sets $h = \delta_e(\varepsilon_{max})$, with ε_{max} maximum energy of electrons reaching the anodic tether-end throughout perijove passes during operation, just hundreds of kilometres above the planet. The result is thin and short tethers, that capture S/C 3 times as heavy, just 200-300 kg, say, allowing for <u>cheap</u> missions [9].

A similar analysis might possibly be applied for other *Giant* planets. Need for reducing costs of space missions has been long a pressing one. The *motto* of *IAF*/*IAC* 2016, in Mexico, is *Making space accessible and affordable to all countries*. NASA's Planetary Science Division has recently considered designing and flying robotic space probes to so called *Ice giants*, Uranus and Neptune, with common space platforms.

Missions to all 4 Giant planets, Jupiter, Saturn, Uranus, and Neptune, face common issues. They are far from the Sun, and present deep gravitational wells, far from the Earth, setting both *power* and *propulsion* issues, if not just flyby missions but to operate through the planet gravitational well. This leads to high cost and a mission-trip issue, the more so for the Ice giants, typically requiring very heavy S/C and very long times. It has been mentioned that the long times for designing, building, and flying such missions make them lie beyond the lifespan horizon of people involved in the missions from start.

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