**Bare-Tether Missions Paradigm for Exploration of Ocean Worlds in Plumes
of Icy Moons *Enceladus*, *Europa*, and *Triton***

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I.- Introduction

The case of *Ice Giants*, which only received flyby missions, is of particular interest as regards exploration. There are multiple issues of interest in exploring Uranus and Neptune as different from Gas Giants: Composition is definitely different; rocky mass-percent is much larger; both planetary dynamics and magnetic structures present striking differences (quite relevant for tether interaction); *exoplanet* statistics suggests Ice types are well more abundant than Gas types. This raises questions about *exomoons* and *exomagnetism*...

As regards considering tethers for a Neptune mission, beyond just a flyby, there would seem to exist a basic problem with standard methods. The *Introduction* section of NASA's "Ice Giants" Pre-Decadal Mission Study Report, JPL D-100520, June 2017 (529 pp), in Sec.2.3.3, recalls the multiple studies, over the last half-century, on mission design options for exploration of Uranus and Neptune, ranging from just chemical propulsion to electric propulsion, both with and without gravity assists, and a variety of mission architectural concepts.

First, such faraway missions appear quite costly. In the Report the estimated cost of a *Flagship* Neptune mission was \$1.972B, \$300M less for Uranus, whereas total budget for both planets was \$2B. Secondly, available solar power is practically nil in a large part of the trip, spacecraft capture by chemical propulsion leading to high wet-mass, with scientific load limited to a small mass fraction, and orbital maneuvers quite reduced after capture. Mission concept typically involves an *orbiter* and an *atmospheric probe*. Main objectives would be setting constraints to the planet interior conditions, including layers structure, with convective *versus* stable regions, bulk composition, and improved knowledge of the dynamo process.

Those objectives could certainly lead to fundamental advances in planetary science, and efforts to carry out such missions will surely be kept, either accepting high costs or finding new ways to reduce them. In particular, *Radioisotope* (plutonium-238 oxide) *power systems* and *Aero-capture* were repeatedly considered to deal with power and propulsion issues but decayed consideration.

II.- A Second Exploration Paradigm

Presently, however, there is an important variant of all *Giants* exploration, involving just *Icy moons* and the *OceanWorld* concept, which are not mentioned in the JPL D-100520 Report. In May 2015 the US Congress approved a bill to finance a new NASA program to explore habitability places in the outer Solar System, with internal oceans that might allow simple forms of life. That led to the *Icy Moons* concept: Life would require source of energy, water, and proper chemistry. The ocean would lie between a rocky bottom, warmed by tidal forces from their giant planets, and a top colder ice shell. In the simplest scheme of *hydrothermal (redox)* processes, water molecules could lose oxygen to *reduced* minerals at the floor and, moving upwards, get again *oxidized* by CO₂ molecules, generating both H₂O and CH₄ (*methanogenesis*).

OceanWorld missions could include Saturn's moon *Enceladus* foremost, a plume at its Southern Pole being explored in the *Cassini* mission [1]; Jovian moon *Europa*, which might also present a plume, as recently suggested from reviews of *Galileo* data, apparently overlooked [2]; and Neptune's moon Triton, where geysers, i.e. plumes, were detected at the *Voyager 2* flyby. Missions minor in a sense, would involve multi-kilometers long electrodynamic bare tethers, the planetary magnetic field allowing free S/C capture and orbital maneuvers for visits to moons.

III.- Bare Tethers and Icy moons

Missions to the Icy Moons may require, indeed, non-conventional concepts. *Electrodynamic Tethers*, being thermodynamically dissipative, do not use propellant and do not need electrical power but can generate it if convenient, when close to the planet [3]. Several *geometrical* issues involved in bare-tether operation would make it effective for *Icy Moons* exploration.

i) Recalling ED-tether basics, the electric field *outside* the tether being negligible in the frame moving with the highly-conductive magnetized plasma, there is an outside motional field $\mathbf{E}_m$ in the tether frame that will drive a current $\mathbf{I}$ inside the tether with $\mathbf{I} \cdot \mathbf{E}_m > 0$. The weakly relativistic transformation of that outside field would read

$$\bar{\mathbf{E}}(\text{tether frame}) - \bar{\mathbf{E}}(\text{plasma frame}) = (\bar{\mathbf{v}} - \bar{\mathbf{v}}_{pl}) \times \bar{\mathbf{B}} \equiv \bar{\mathbf{E}}_m \quad (1)$$

where $\mathbf{v}$, $\mathbf{v}_{pl}$ are velocities of S/C and local co-rotating plasma, and $\mathbf{B}$ is the planetary magnetic field. The Lorentz force $L \mathbf{I}_{av} \times \mathbf{B}$ on a tether of length L with length-averaged current $\mathbf{I}_{av}$, involving field $\mathbf{B}$ twice makes its thermodynamic character manifest.

Planetary capture requires long enough tether and effective electric contact with the low-density N_e ambient plasma, to efficiently collect electrons for substantial current $\mathbf{I}$ and subsequent Lorentz drag. Tethers in *Low Earth Orbit* faced this same issue around 1990, for de-orbiting operations. The standard concept was a conductive sphere at the anodic end A of a tether fully insulated all along. The bottleneck was that local Debye length $\lambda_D \propto \sqrt{(T_e/N_e)}$ and electron gyroradius $l_e \propto (\sqrt{T_e})/B$ are so small (of order of centimetre) compared to any useful 3D passive collector that both electric shielding and magnetic guiding greatly reduce collection.

The anodic-contact issue was solved in the early 90's by eliminating the sphere and leaving the tether *bare* of insulation to allow it collect electrons itself over the segment resulting positively polarized, as a giant cylindrical Langmuir probe in the optimal *OML (orbital-motion-limited)* regime [4]. This is replacing 3D collection with single dimension many times λ_D and l_e by 2D collection with two disparate dimensions, one being the kilometres-long anodic tether segment, providing large collecting area, and another, comparable to λ_D and l_e , characterizing collection in planes perpendicular to the tether. Except that the Jovian magnetic field is 20 times larger than the magnetic fields of Earth, Saturn, and Neptune, the above anodic-contact solution applies at the different planetary captures to consider. We just advance here that the bare tether concept presents a further convenience to be discussed in Sec. V.

ii) It is important determining the relative convenience of different cross-section shapes and the parametric domain of validity of the OML law. Laframboise and Parker had proved that OML currents to cylindrical probes of convex cross-section and equal perimeter p are equal [5]. At probe bias ΔV high enough, ($e\Delta V \gg$ energy of ambient electrons, as at planetary capture), the OML law takes the simple form

$$I_{OML} \approx eN_e \times L \frac{p}{\pi} \sqrt{\frac{2e\Delta V}{m_e}} \propto p \quad (2)$$

This suggests using tethers with thin-tape cross-section.

A fair comparison considers *corresponding* tethers, with equal length and mass, and thus equal convex cross-section area for equal materials. This results in equal electric resistance and maximum *short-circuit limited* current density αE_m (α = tether conductivity) and Lorentz drag. The tape, however, has much greater perimeter and thus collection capability and faster maneuvering at low plasma density N_e , than a round wire; a tape can reach maximum current with current in the wire well below maximum. An alternative convenience: for equal perimeters, tapes are much lighter. Also, they involve 3 disparate lengths, thickness $h \ll$ width $w \ll$ length L , easing scalable design. Actually, however, tapes never collect *OML current* due to potential barriers in the vicinity of flat collecting surfaces, though effects are weak, typically about 1% [6].

In absence of magnetic field, an asymptotic analysis of current collection by a cylinder of radius R at potential bias $\Phi(R)$ determined the complex 2D profile $\Phi(r)/\Phi(R)$ versus R^2/r^2 , first introduced in the literature in [6]. Maximum, *Orbital Motion Limited*, current collection required $\Phi(r)/\Phi(R) \geq R^2/r^2$ throughout. The OML law was found to hold for R below certain maximum

value $R_{max} [e\Phi(R)/kT_e, T_i/T_e]$ of order of λ_D , a result needed for design considerations. Current keeps close to maximum for some definite parametric domain, which allows useful tether operation in orbit raising or lowering, when both T_e/T_i and λ_D are varying [7].

The limit of OML validity for a thin-tape was also readily determined. At high bias, space charge has weak effect in a large neighbourhood of the probe, where the Laplace equation would apply, but weak screening leads to much larger plasma-sheath size. A tape may be approximated by a straight segment, which is the limit of a family of co-focal ellipses. Solving the Laplace equation in elliptical coordinates, the potential takes a limit form far from the probe, where ellipses approach circles, but well within the sheath. One then finds $w_{max} = 4R_{max}$ [6].

In the presence of a magnetic field, maximum current reads, at high bias,

$$I_{PM} \approx I_{OML} \sqrt{\pi/2} \times (l_e/R),$$

which is the *Parker-Murphy* upper bound to current in a magnetized plasma [6]. A large enough l_e/R ratio together with values $R/\lambda_D = O(1)$ make current collection not sensitive to geomagnetic effects. Effects from the magnetic (*self*-) field locally generated by the tether current were shown to be much weaker for tapes as compared to round wires [8].

(iii) As regards cathodic contact, the current of attracted ambient ions arriving at a negatively polarized segment is very small because of the very large ion-to-electron mass ratio; with ions leaving as neutrals, the cathodic electron current, though enhanced by secondary emission, is then too low to be effective. The standard device for effective cathodic contact is a *Hollow Cathode*, which ejects electrons within a neutral expellant cloud, with little voltage-bias required; it has a very low contact impedance, and is easy to switch on and off. Typically, this would represent a negligible use of consumables. If that is not the case, however, one might use a *no-consumables* tether by coating aluminium with recently available materials having very low *Work Function*, of order of 1 eV [9]. This would result in substantial thermionic emission at working temperatures. A tether segment extending from anodic end *A* to a zero bias point *B*, collecting electrons in the OML regime, would be followed by a complex cathodic segment.

In general, as bias becomes more negative in moving from *B* to cathodic end *C*, one would first find *space-charge-limited* (SCL) emission covering up to some intermediate point *B**, then full *Richardson-Dushman* emission from *B** to *C*. SCL emission in the presence of the attracted ambient ions generates a generally unresolved *double-layer* structure in front of the cathodic tether-segment. An approximate analysis of the SCL structure [10] allowed determining limit parametric regimes, one where RD emission is not reached, another with short SCL segment and negligible contribution to total current, making possible to skip its modeling [11].

IV.- Validation of Bare-Tether Analysis

Bare-tether theory was validated in space in an unintended way. Measurements at the *International Space Station* in early 2001, involving 3 NASA Centers, NOAA/Boulder, Univ.Houston and SAIC, showed on-board plasma-contactors, which would eject electrons if ISS structure became too negative, were indeed ejecting substantial current under no sensible ambient conditions [12]. Authors acknowledged in the Abstract, explaining substantial current data, that tensioning rods of solar array masts could collect ambient electrons as *bare-wire* tethers, with modeling “*based upon J.R.Sanmartin’s bare wire collection theory*”, which was incorporated into the complex ISS computer code, *Environment Work Bench*, that includes models of the *Station* geometry, orbital motion, earth’s magnetic field, and ionosphere.

Further, in 2007, *Vlasov*-code simulations in the high-bias OML regime, at a University of Michigan PhD Thesis by E. Choinière on the density profile $N_e(r)/N(\infty)$ versus $\ln(r/R)$ were shown to agree to a very high approximation, when compared [13], with previous detailed

analytical results in corresponding features at the $\Phi(r)/\Phi(R)$ versus R^2/r^2 profile in [6]. The *bare-tether* concept can now be considered a successful paradigm in ED-tether operation.

V.- The Planetary Plasma-Density Issue

In the Lorentz drag, $L \mathbf{I}_{av} \times \mathbf{B}$, the length-averaged current involves both ambient magnetic field and plasma density, $I_{av}(\mathbf{B}, N_e)$ along the S/C trajectory. Field $\mathbf{B}$ of all 4 Outer Planets has been reasonably well determined through faraway measurements, but this is not the case for plasma density N_e , as a ‘field’ describing a *continuous medium*, except for Jupiter, by way of modeling abundant *Galileo*-mission in-situ data. This is more critical for the Ice Giants, which have been visited by just *flyby* missions. Fortunately, bare-tether operation analysis can deal with ill-defined density profiles by appealing to long enough tapes, *also explaining why bare tethers can be fairly insensitive to regular drops of plasma density along orbit* [6].

A bare tether accommodates density variations by allowing the *anodic* segment to self-adjust by varying its fraction of tether length, being larger the lower N_e . This could make a broad range of N_e values lead to length-averaged current near the *short-circuit* maximum $wh \times \sigma_t E_m$ (a design reference-value independent of actual electron densities), for a convenient range of L values, not affecting tether mass if just width w is reduced at fixed thickness h .

In the OML electron-collection regime, the length-averaged tether current can be written

$$I_{av} = wh \sigma_t E_m \times i_{av}(L/L_*), \quad (3)$$

$$L_* \propto E_m^{1/3} (\sigma_t h / N_e)^{2/3} \quad (4)$$

where L_* is a characteristic length gauging bare-tether electron-collection impedance against ohmic resistance, and increasing with decreasing N_e [14]. The dimensionless average-current $i_{av} < 1$, which vanishes with length ratio L/L_* , approaches 1 at large L/L_* following the approximate simple law,

$$i_{av} \approx 1 - L_*/L, \quad \text{for } L/L_* > 4, \quad (5)$$

in the *HC* case, neglecting *HC* impedance (and cathodic electron current) [14]. Equation (5) does clearly show *OML*-current accommodation to drops in electron density. Indeed, consider L/L_* decreasing from 20 to 4, say, with tether length L and parameters in (4), other than N_e , constant. Value of N_e itself would then be lower by a 0.09 factor, whereas current i_{av} in (5) would just slightly decrease from 0.95 to 0.75. In case of thermionic emission, *SCL* and *RD* segments play both ion current and *HC* roles.

Results are solution to equations describing the variation of tether current and bias along the anodic segment,

$$\frac{dI}{ds} = eN_e \frac{2w}{\pi} \sqrt{\frac{2e\Delta V}{m_e}}, \quad \frac{d\Delta V}{ds} = \frac{I}{\sigma_t hw} - E_m \quad (6 \text{ a, b})$$

with distance s from anodic end A , considering (as in general bare-tether analysis) that the extremely large ratio L/w allows assuming that each tether point would collect current as if it were part of a cylinder uniformly polarized at the local tether bias.

It is worth emphasizing that the standard tether model previous to the bare-tether concept, with electron collection by a given spherical conductor, could not deal this way with similar lack of detailed information on ambient plasma density. Also, *aerocapture* operation in *Giants* exploration can neither deal with lacking detailed information on planetary atmospheric medium. Hence, bare-tether capture is not like *aerocapture*, which NASA repeatedly considered using.

VI.- New Paradigm in Exploring Icy Moons of Outer Giant Planets

The planetary interest on *search for life* outside Earth set emphasis on *Icy moons exploration* as paradigm. As we shall notice in the following, this fits perfectly with using tethers for such missions, now involving two stages, but just an *orbiter*:

- 1) The first stage would indeed be capturing the S/C into an orbit with periapsis in the ionosphere, very close to the planet.
- 2) The second stage would be lowering the apoapsis to allow a sequence of flybys of moons of interest.

Note that this planetary search would also apply to moons of Jupiter and Saturn. Also, at difference with a planet flyby, any such *moon flyby* is part of a bound orbit of its planet and does not preclude further flybys.

The magnetic field of *Outer Giants* is characteristically due to currents from charges repeatedly moving in some *small volume* well inside the planet. Outside, thus at ‘large’ distances from the system of steady currents, but close to the planet, the field is usually described through the universal *magnetic-moment* vector concept and its simple dipole-law approximation. A magnetic moment $\mathbf{m} = m\mathbf{u}_m$ of magnitude m (*gauss* $\times$ *meter*³) and unit vector $\mathbf{u}_m$, located at a ‘point’ $\mathbf{r}_m$, gives a definite magnetic field at a ‘faraway’ point $\bar{\mathbf{r}}$,

$$\bar{\mathbf{B}}(\bar{\mathbf{r}}) \approx \left[3(\bar{\mathbf{u}}_\rho \bullet \bar{\mathbf{m}})\bar{\mathbf{u}}_\rho - \bar{\mathbf{m}} \right] / \rho^3 \quad (7)$$

with $\bar{\rho} = \rho\bar{\mathbf{u}}_\rho \equiv \bar{\mathbf{r}} - \bar{\mathbf{r}}_m$ vector position in planetary frame with displaced origin. For **Saturn**, $\mathbf{m}$ is at its centre ($\mathbf{r}_m \approx 0$, $\bar{\rho} = \bar{\mathbf{r}}$) and near parallel to its rotation axis, conditions reasonably holding for Jupiter too. At points in a *circular equatorial orbit*, the field would, then, just read $\bar{\mathbf{B}}(\bar{\mathbf{r}}) = -\bar{\mathbf{m}}/\rho^3$, the Lorentz drag on a tether, orbiting vertical, being parallel to the velocity.

Lorentz drag (and power) decreasing as $1/r^6$ with increasing distance r from the planet center, most efficient capture would require periapsis just “outside” the planet, radius r_p satisfying condition $r_p \approx R_{pl}$. Note that drag at, say, $r_p \approx 2R_{pl}$, would be lower by a 0.0156 factor, or 2 orders of magnitude. Further, drag might only be effective in a short orbital arc around periapsis.

Hence, if tether current is kept following capture, and in several periapsis passes, effect on periapsis would be weak. Apoapsis would be lowered, however, in seeking flyby of any particular moon. Switching then tether current off, could allow additional moon exploration. Such orbital maneuvers, involving dissipation, are free for tethers, a case opposite conditions for maneuvering in the planned NASA mission.

Mission operation could next go to moon of interest closer to the planet, corresponding to lower S/C specific energy. The general relation between specific energy ε and eccentricity e in the 2-body problem of S/C and planet with gravitational constant μ , at (near-) constant r_p ,

$$\varepsilon = \mu_{pl}(e - 1)/2r_p,$$

is a near-linear one, yielding a simple sequence of eccentricities following capture.

For Neptune (and Uranus) $\mathbf{m}$ is well off center, and $\mathbf{u}_m$ has a complex orientation, the dipole approximation for field $\mathbf{B}$ in Eq.(7) failing over a range of points close to the planet, multipole terms being required for an accurate description. For very simple *Neptune* estimates, one might use a description involving a *magnetic moment* with $0.55 R_N$ offset, and 47° tilt to the planet rotation axis, and field $\mathbf{B}$ decreasing as $1/\rho^3$. Capture *efficiency* would be greatest for the S/C facing $\mathbf{m}$ at periapsis.

VII.- *Enceladus* Exploration

Brent Sherwood, at the *Jet Propulsion Laboratory/California Institute of Technology*, discussed an strategic map in the search for life outside Earth [15]. Among the many *Ocean Worlds* of our solar system, he promotes *Enceladus* as unique in its combination of astrobiological relevance and exploration-worthy attributes: extensive liquid-water ocean with *hydrothermal* activity, openly accessible at its south polar *plume*. A roadmap is considered essential to build consensus on funding such ambitious exploration, from start with a *cost-capped* mission, to eventually

reaching plume vent and oceanographic exploration, *each mission step if justified by results from previous steps.*

But he also emphasizes that “the Mars exploration-program precedent demonstrates that an optimistic spirit of exploration can win a sustained line-item program in the NASA budget”; it further helps “a willingness - as Mars exploration has enjoyed - *to aim for the fences*“. And he also “defends cultivation of mutually beneficial partnerships with international space agencies”. About one year later (April 2017), J. H. Waite and 12 co-authors found evidence for H_2 molecules in the *Enceladus* plume [1]. In January 2019, a long paper by 28 co-authors from 16 American Centers [16], summarized Icy-Moons pending work, “*The NASA Roadmap to Ocean Worlds*” *Mission Scenarios* start with *Enceladus*, its *habitability* well established by *Cassini*, proposing mission steps: i) Plume flyby with modern instruments (*in situ* analysis); ii) Flyby + sample return to allow analysis back at Earth; iii) *Lander*, iv) *Crawler* (maybe combined); v) *Submarine* to access the ocean, reaching its floor to check presence of, and collect samples from, hydrothermal vents. Recalling the Sherwood map, emphasis is placed on minimizing “the number and scope (and therefore cost) of missions needed to address the question... is there life on *Enceladus*?”

There is a variety of proposed missions to *Enceladus*. The *Enceladus Explorer*, funded by the German Aerospace Center (DLR), would use a 5 kW nuclear reactor providing power to an electrical thruster for both transfer to Saturn plus orbit insertion, and to a subsurface maneuverable ice-melting probe, the *Ice Mole*, to explore the *Enceladus Ocean* below the south pole plume [17]. The *Enceladus Life Finder* [J.I.Lunine, J.H.Waite, F.Postberg, L.Spilker, and K.Clark, 46th Lunar and Planetary Science Conference (2015)], would be a Discovery class mission with 325 W solar power. In the **THEO Mission Concept** [K. K. John and 19 co-authors from 15 US Centers, 47th Lunar and Planetary Science Conference (2016)], of *New Frontiers* class, the spacecraft would use 72 m² solar arrays for 594 W power, and 1 Venus and 2 Earth gravity assists to ease propulsion, allowing 10 years trip, about 4 years longer than a direct Hohmann transfer to Saturn.

A minor electrodynamic-tether mission, at most of *Discovery* class, quite capable of placing a S/C with a set of instruments at a convenient orbit location at Saturn, might fit the *cost-capped* start-step of the Sherwood map. **It is a fortunate fact** that an elliptical Saturn orbit with apoapsis at the circular *Enceladus* orbit and periapsis just outside Saturn (as fitting optimal tether capture), with excentricity 0.59, is in a 1:2 Laplace resonance, allowing repeated, tangent, slow flybys of the moon [18]. If *Enceladus* was closer to Saturn, no such simple resonance would be possible; if farther, no tangent, slow flybys would be possible. This mission would be quite relevant for American and European groups that worked on *Cassini* results but are lacking a new mission to *Enceladus*.

VIII.- Europa and Triton explorations

Regarding *Europa*, intended NASA’s *Clipper* and ESA’s JUICE missions, not fitting the overall missions map, might be replaced by a mission to explore *Europa*’s plume, if it indeed exists, as mentioned in Sec. II.

As regards *Triton*, the Neptune magnetic field is as weak as the field of Saturn, and Neptune is much farther, but capture efficiency might be made much greater due to its large $0.55 R_N$ magnetic-moment m offset. Field B decreasing with distance to m as inverse 3th power, the S/C would need be facing the *offset* when reaching *periapsis*, as mentioned in Sec. VI [19].

Basic science-goals of a *Triton* mission would include repeated moon flybys, in retrograde orbit. Both the slow Neptune spin and its high density (which makes for fast S/C motion around a periapsis if close), mean Neptune would rotate little during the short capture-arc, resulting in

about equal efficiency for prograde and retrograde captures. Also, retrograde orbiting means that Triton tides due to its planet would provide for strong hydrothermal processes.

Serious issues in NASA planning of Uranus and Neptune missions are not present in tether missions. Beyond neither power needs nor propellant issues being relevant, magnetic capture involving plasma density, well above the atmosphere, does not give rise to serious heating, which would otherwise require a thermal-protection system.

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