A Minor Mission to *Ice Giant* Neptune

Juan R. Sanmartin and Jesús Peláez

ETSIAE, Universidad Politécnica de Madrid

I. Introduction

Broad missions *Cassini*, at *Saturn*, and *Galileo* and now *Juno*, at *Jupiter*, provided deep overall knowledge about the *Gas Giants*. For minor missions involving specific visits, like exploring moon *Europa* at *Jupiter*, or maybe *Enceladus* in the *Saturn* case, electrodynamic tethers, which are thermodynamic in character and can provide free propulsion and power for capture by a planet, followed by free maneuvering for exploration, could make for more than '*orbiter*' missions.

The two *Ice Giants*, *Uranus* and *Neptune*, have been considered by NASA as *flagship* missions for the next decade (*Ice Giants Pre-decadal Survey Mission Study*, http://www.lpi.usra.edu/icegiants/mission_study/Full-Report.pdf).

There are multiple issues of interest in exploring *Ice*, as different from *Gas*, Giants:

--Composition is definitely different, Jupiter and Saturn being made almost entirely of hydrogen and helium, Uranus and Neptune containing substantial amounts of oxygen, nitrogen, carbon…

--The planetary magnetic-field structure shows a striking (and very important for tether interaction) difference, as detailed below.

--The rotation axis of Uranus lies in the ecliptic plane itself, and Neptune, as opposite the other Giants, has just one large moon, *Triton*, which is in retrograde orbit, either fact being possible sign of collision with other big bodies in the intriguing, early Solar System dynamics.

--*Exoplanet* statistics suggest *Ice* types are much more abundant than *Gas* types…

We here discuss whether tethers might be used for a minor mission to *Neptune*. As in the Saturn case tethers could appear inefficient as compared with Jupiter, because the magnetic field $\boldsymbol{B}$ is similarly small, the spacecraft-capture efficiency (*S/C-to-tether mass ratio*) going down as B^2 for weak fields: The S/C relative velocity $\boldsymbol{v'}$ induces in the co-rotating, magnetized ambient plasma a *motional field* $\boldsymbol{E}_{ind} \equiv \boldsymbol{v'} \wedge \boldsymbol{B}$, *in the S/C reference frame*, and $\boldsymbol{B}$ exerts *Lorentz* drag per unit length $\boldsymbol{I} \wedge \boldsymbol{B}$ on tether current $\boldsymbol{I}$ driven by $\boldsymbol{E}_{ind}$.

It has been shown, however, that efficiency for Jupiter is less than expected because of its very high $\boldsymbol{B}$ itself, which might result in too strong tether heating and/or energetic attracted electrons crossing the tether tape and missing collection. This requires design with limited tether length, to keep *length-averaged current density* well below its maximum, <u>short-circuit</u> value $\sigma_c E_{ind}$ due to ohmic effects and just proportional to *B*, limiting efficiency. For weaker field ***B***, tethers avoid those issues, current-density reaching near the particular short-circuit maximum. Capture efficiency is around 3.5 for Jupiter and Saturn [1], [2].

II. The Neptune environment

Tether operation depends on both magnetic field and plasma density N_e , required/available information for either having quite different character. Field ***B*** of *Giants* is due to currents from charges repeatedly moving in some small volume inside the planet. The field outside, thus at 'large' distances from the system of steady currents, is generally described through the *magnetic-moment* vector concept and its dipole law approximation:

----

[1] J.R.Sanmartin *et al*, Electrodynamic Tether at Jupiter. I. Capture Operation and Constraints, *IEEE Transactions in Plasma Science*, **36**, 2450-2458**,** *doi:* 10.1109/TPS, 2002580, 2008; J.R.Sanmartin *et al*, Analysis of Tether-mission Concept for Multiple Flybys of Moon Europa, *Journal of Propulsion and Power*, **33**, 338-342, *doi*: 10.2514/1.B36205, 2017.

[2] J.R.Sanmartin, J.Pelaez, and I.Carrera-Calvo, Comparative *Saturn*-versus-*Jupiter* Tether Operation, *Journal of Geophysical Research-Space Physics*, **123**, 6026-6030, *doi*: 10.1029/JA025574, 2018

A magnetic moment $\boldsymbol{m} = m\boldsymbol{u_m}$ of magnitude m (*gauss* × *meter*^{3}), *unit vector* $\boldsymbol{u_m}$, located at a 'point' $\boldsymbol{r_m}$, gives a magnetic field at a 'faraway' point $\overline{r}$ [3],

$$\overline{B}(\overline{r}) \approx \left[3(\overline{n}\cdot\overline{m})\overline{n} - \overline{m}\right] / \rho^3$$

where $\overline{n}\rho \equiv \overline{r} - \overline{r}_m$. For Saturn, $\boldsymbol{m}$ is at centre ($\boldsymbol{r_m} \approx \boldsymbol{0}$) and parallel to its rotation axis (as also roughly holding for Jupiter). At points in a circular, equatorial orbit, the field reads $\overline{B}(\overline{r}) = -\overline{m}/r^3$ ($m_S = 0.21G{\times}R_S{}^3$) and the Lorentz force on a tether orbiting vertical is opposite the velocity.

The case of Neptune, with $\boldsymbol{r_m}$ off-centre, is sensibly more complex. The dipole law is roughly valid for $r/R_N > 3$, distances that are of no interest for tether applications. For $R_N < r < 3R_N$, *quadrupole* and *octupole* terms (that decrease faster with distance) and/or differently localized current sources, might need be considered [4]. In this preliminary analysis of just S/C capture, we only use an approximation to the dipole term (having $m_N = 0.13G{\times}R_N{}^3$), itself complex in both location $\boldsymbol{r_m}$ and orientation $\boldsymbol{u_m}$.

----

[3] L.D. Landau and E.M. Lifshitz, The Classical Theory of Fields, Pergamon Press, Secs. 43 and 44, 1962.

[4] N.F. Ness, M.H. Acuña, and J. E. P. Connerney: Neptune's Magnetic Field and Field-Geometric Properties'. In *Neptune and Triton*, ed. D. P. Cruikshank (Tucson: Univ. of Arizona Press), pp.141-168, 1995.

Faraway measurements did yield thorough description for B, but not for plasma density. Data from the *Voyager 2* 1989-flyby did not yield definite models of the ambient magnetized plasma the tether would be operating in. In-situ measurements by the *PLS* instrument [5] at the closest approach, $r \approx 1.18 R_N$, showed $N_e \approx 2$ cm^{-3}, orders of magnitude below observational data from (*whistler*) waves emitted from the plasma [6]. The flyby allowed *S/C* occultation by Neptune, *radio-occultation* data showing similar disagreement [7].

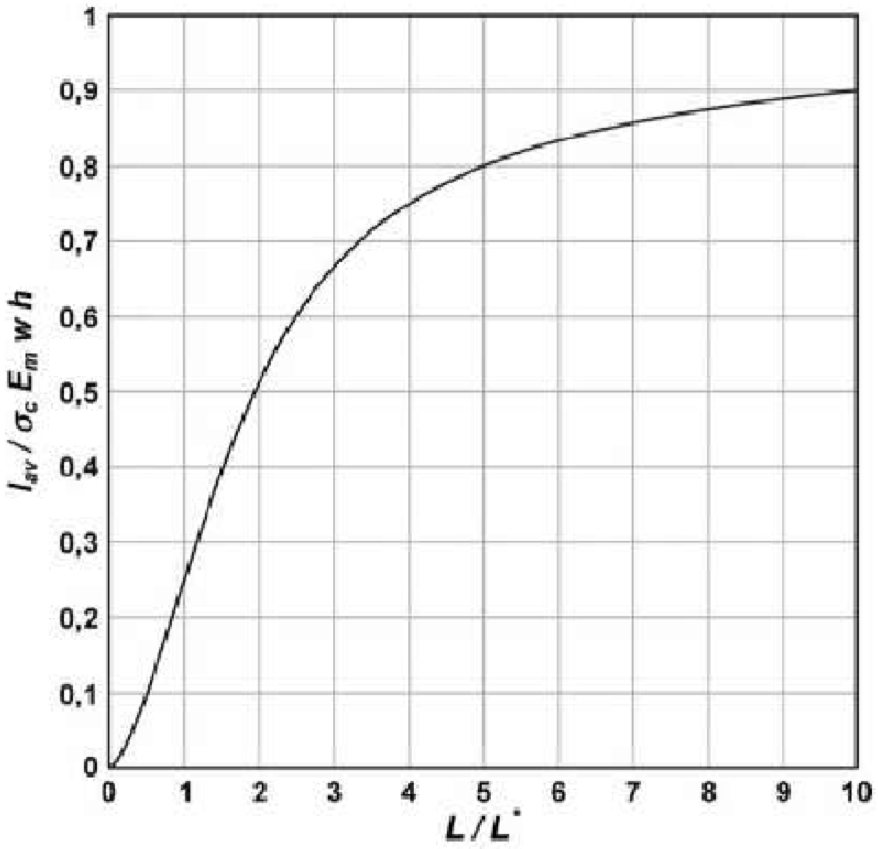
That may not be a problem, however, a reasonable range of density values leading to current-densities near the short-circuit maximum, for appropriate tether lengths (not affecting tether mass, if tether-tape width w is adjusted). The length-averaged tether current I_{av} approaches the short-circuit value $\sigma_c E_{ind} \times wh$, which is independent of actual plasma density, at large L/L_* (Fig.1), with tether *scale length* L_* proportional to $E_{ind}^{1/3}(\sigma_c h/N_e)^{2/3}$. In general, electron-collection by a tether accommodates density drops (Fig.2):

----

[5] J. D. Richardson, J. W. Belcher, and R. L. McNutt: The Plasma Environment of Neptune. In *Neptune and Triton*, pp. 279-340.

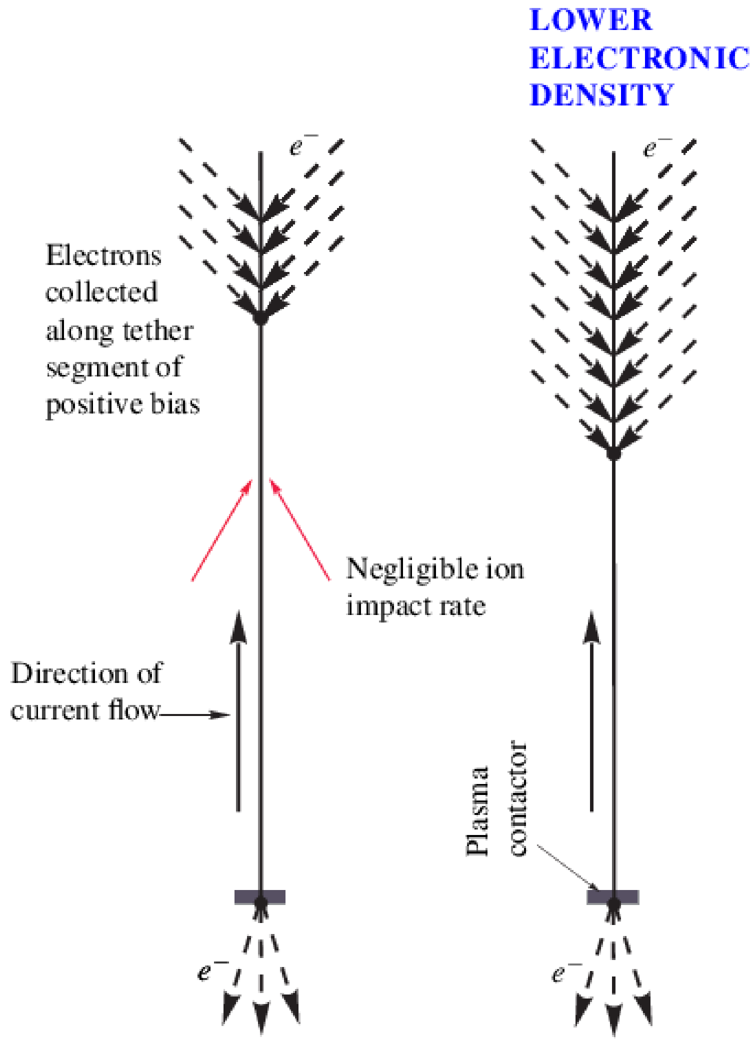
[6] D. A. Gurnett and, W. S. Kurth: Plasma Waves and Related Phenomena in the Magnetosphere of Neptune'. In *Neptune and Triton*, pp. 389-423,

[7] G. F. Lindal: The Atmosphere of Neptune. 'An Analysis of Radio Occultation Data Acquired with Voyager 2'. *Astronomical Journal*, **103**, pp. 967-982, 1992.



$I_{av} / \sigma_c E_m w h$
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0 1 2 3 4 5 6 7 8 9 10
L / L^*

Fig. 1



LOWER
ELECTRONIC
DENSITY
e^-
Electrons collected along tether segment of positive bias
Negligible ion impact rate
Direction of current flow
Plasma contactor
e^-

Fig. 2

III. Magnetic S/C capture

Most relevant differences in Neptune magnetic environment are large dipole *offset*, $0.55R_N$, and tilt, $47°$ with respect to the planet rotation axis. In the OTD2 *offset-tilted* model [4], the dipole is located $0.19R_N$ below the equatorial plane and $0.52R_N$ radially away from the axis, in the plane containing rotation axis and dipole, with $\boldsymbol{u_m}$ inclined 22° with respect to that meridian plane. In this preliminary estimate, we use the dipole approximation near the planet, for simplicity, and ignore both distance $0.19R_N$ and dipole tilt, along with the $22°$ angle. We consider Neptune capture as presenting just a $0.5R_N$ *offset*.

For the hyperbolic orbit of a S/C in direct *Hohmann* transfer from heliocentric circular orbit at Earth to circular orbit at Neptune, the velocity in the Neptune frame would be v_∞ = 3.96 km/s. Further, *Lorentz drag* being quadratic in the planetary dipole field, thus decreasing as $1/r^6$ with distance and having limited radial reach, requires *periapsis* very close to the planet, as for Jupiter and Saturn cases, $r_p \approx R_N \approx 24765$ km.

The incoming hyperbolic eccentricity e_h, is then very close to unity,

$$e_h - 1 = v_\infty^2 r_p / \mu_N = 0.058, \qquad (\mu_N \approx 6835107\ km^3/s^2)$$

The orbit that results from Lorentz-drag capture being barely elliptical (e just below unity), calculations may use a parabolic orbit throughout, with no sensible change except the dramatic one from open to closed orbit. Independently, because drag operates near periapsis, there is little change of r_p in capture and following tether maneuvering.

Because of the strong dipole offset, the S/C should best reach periapsis when crossing the meridian plane that contains the dipole center. This would result in the dipole optimally facing the S/C when at periapsis. That meridian plane has been reasonably well determined; also, when observed from away, Neptune keeps announcing its orientation with its stunning magnetic-structure rotation.

A simple estimate of capture efficiency just requires that dissipative Lorentz work, over an appropriate drag-arc Δs around periapsis conditions, makes orbital energy negative,

$$\sigma_c E_{ind} wh \times LB \times \Delta s > \frac{1}{2} M_{SC} v_\infty^2, \qquad E_{ind} = v' B \approx v_{SC} B$$

using $v_{SC} = (2\mu_N / R_N)^{1/2} \approx 23.5$ km/s >> co-rotation velocity $2\pi R_N / 16.7$ h ≈ 2.6 km/s, yielding for *Al*

$$\frac{M_{SC}}{m_t} < \frac{2\sigma_c v_{SC} B^2}{\rho_t v_\infty^2} \Delta s \approx 38.9 \frac{ms}{kg\Omega} \times B^2 \Delta s$$

where $B = B_p(gauss) \times 10^{-4}$ volt s/m^2 and $\Delta s = C\,|\bar{r}_p - \bar{r}_m|$, C a factor about 2 / 2.5.

If Neptune lacked offset, we would have $\Delta s \sim 2.5\ R_N$ and $B_p\,(gauss) = 0.13$, yielding $M_{SC}/m_t < 0.41$, which is one order of magnitude below Saturn's [2]. This arises from the Saturn-to-Neptune $(0.21/0.13)^2$ $B_p^{\,2}(gauss)$ ratio; a Saturn *tail-flyby* gravity-assist by Jupiter; and Saturn's lower density and faster spin. A $0.5R_N$ offset, now, decreases Δs by a factor 1/2 and increases $B_p^{\,2}$ by a 2^6 factor, overall increasing efficiency to a value $0.41 \times 32 \approx 13.1$, or a full half-order of magnitude above Saturn efficiency.

The above convenient synchronism is somewhat tempered by Neptune having slow spin and high density, making orbital motion of a SC fast. Time for the SC to go from point a to point b in the orbit, rotating 90°, is $0.78\ h$. During that time the meridian plane containing the dipole centre could rotate just 16.8° (Fig.3).

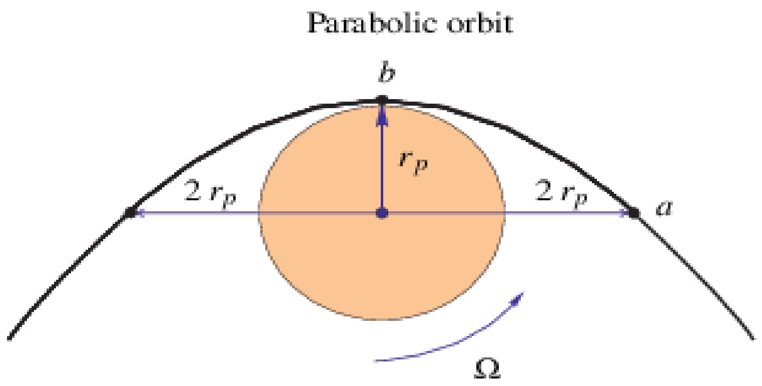


Fig.3

We used above that conditions of low planet density correspond to slow orbital motion of a S/C in *low* parabolic orbit, case of Saturn, and fast orbital motion corresponds to high planet density, case of Neptune. This follows from the orbit equations

$$v = \sqrt{\frac{2\mu}{r}}, \quad 1 + \cos\theta = \frac{2r_p}{r},$$

and the resulting Barker equation giving time t from periapsis-pass versus radius

$$\frac{3v_p}{2r_p}t = \left(2 + \frac{r}{r_p}\right)\sqrt{\frac{r}{r_p} - 1}$$

The characteristic time of the S/C motion is thus of order

$$\frac{r_p}{v_p} = \frac{r_p}{\sqrt{2\mu/r_p}} = \sqrt{\frac{r_p^3}{2GM_{pl}}} \propto \frac{1}{\sqrt{\rho_{pl}}}$$

for $r_p \approx R_{pl}$.