Planetary exploration of Saturn moons Enceladus and Dione

J.R. Sanmartín^{a,b}, J. Peláez^{b,*}

^a Real Academia de Ingeniería of Spain, Spain

^b Universidad Politécnica de Madrid, Pz. C. Cisneros 3, Madrid, 28040, Spain

ARTICLE INFO

Keywords:

Outer giants

Icy moons

Electrodynamic tethers

Magnetic capture

ABSTRACT

Search for habitability in *Outer Planets* moons, requires presence of proper chemistry, water, and energy. Dissipation from tidal forces is major energy source in evolution of *Icy moon* systems, generically exhibiting a multi-layer structure, with outer solid (ice) and intermediate liquid layers, and solid (rocky) core. Saturn moon *Enceladus* has been found to eject plumes of water vapour and ice, and very recently, *hydrogen molecules*, a tentative sign of chemistry supporting microbial life. Purpose of the present work is a preliminary design of a minor electrodynamic tether mission to visit Enceladus. Free tether capture and maneuvering would take the S/C to a Saturn orbit with periapsis very close to the planet and apoapsis at Enceladus orbit, the S/C proved to be then in a 1:2 resonance with the moon, allowing parallel, conveniently slow flybys. Such mission could also involve visiting *Dione*, the 4th largest Saturn moon, Enceladus and Dione being in a natural 1:2 Laplace resonance; it was recently brought to light that Dione exhibits multiple, parallel color lines, hundred kilometers long.

1. Introduction

Search for habitability in moons of *Outer planets* requires presence of sources of energy. Dissipation from tidal forces is a major energy source in evolution of *Icy moon* systems. Heating always accompanies dissipation but, in case of tidal heating, it will additionally present complex spatial distribution, reflecting on a multi-layer structure in the particular case of *Icy moons*. Subsurface oceans are a generic feature of large icy bodies at some point in their evolution. A standard interior model consists of an outer solid (ice) layer, an intermediate liquid layer, and a solid (rocky) core.

It was recently discovered that a Saturn moon, Enceladus, ejects plumes of water vapour and ice particles, evidence of a liquid water reservoir below the surface, in the *South Polar Terrain* [1]. More recently, in the Spring of 2017, it was found that such plumes contain molecular hydrogen, considered sign of chemical reactions supporting microbial life [2,3]. Exploration of Enceladus would appear now of the greatest interest in the search for habitability in the Solar System.

As a moon rises a tide on its planet, they exchange angular momentum, affecting satellite orbit and planet spin; the moon gains orbital energy at the expense of the planet rotational energy. In case of planets with several moons, a complex 3-body paradigm, *Laplace* resonance, involves two (or more) moons of a planet, forming by differential expansions of orbits due to tidal torques. At Jupiter, moons Io, Europa,

and Ganymede are in 1:2:4 resonance, as established by P.S. Laplace at around the birth of *thermodynamic* science.

Enceladus is in a 1:2 resonance with the 4th largest Saturn moon, Dione; Enceladus revolution and rotation periods are both 1.370 days, Dione's periods being approximately 2.74 days. Dione itself became "moon of interest" very recently, in the Fall of 2018, when it was brought to light a feature, observed in the course of the Cassini mission: Dione exhibits multiple color lines (*linear virgae*), like hundred kilometres long, parallel to the equator as latitudinal lines in a map [4]. It was suggested that such linear virgae are possibly due to impacts from dust-sized *foreign* material, with low mass and velocity to form streaks, while depositing onto the surface rather than forming craters.

A minor tether mission could allow exploring this Laplace resonance. Tethers can provide free propulsion and power for capture and then maneuvering, allowing frequent flyby-visits to selected moons, as suggested to explore Jovian moons [5]. *Apoapsis* lowering operation would follow capture, in equatorial orbit, by *Saturn* [6]. As recalled in Sec. 2, tether Lorentz-drag is such that periapsis in the orbit of capture must be very close to the planet, making periapsis itself weakly affected by maneuvering to follow. In Sec. 3 it is shown that this makes quite effective exploration of Enceladus: a S/C with periapsis very close to Saturn and apoapsis at Enceladus orbit, is in 1:2 S/C-Enceladus resonance itself, allowing tangential, conveniently slow flybys of the moon.

Following capture by Saturn, repeated Lorentz force around periapsis may bring the apoapsis first to an elliptical orbit at 1:1 resonance with Dione. After a number of flybys, with its *Hollow Cathode* off to explore Dione, as had been suggested for a minor tether mission to moon Europa [7], repeated tether operation might bring the apoapsis down to reach a resonance with Enceladus, for parallel flybys. Section 4 shows that Lorentz-drag peaking at periapsis greatly simplifies the analysis, and tether operation in touring Enceladus and Dione is explicitly determined. Results are discussed and conclusions summarized in Sec. 5.

2. Saturn versus Neptune capture review

Tether efficiency in spacecraft-capture (*S/C-to-tether mass ratio*, M_{SC}/m_t) goes down as B^2 for weak magnetic fields, because field $\mathbf{B}$ is twice involved: $\mathbf{B}$ exerts Lorentz force per unit length $\mathbf{I} \wedge \mathbf{B}$ on tether current $\mathbf{I}$, actually driven by a *motional* electric field $\mathbf{E}_m \equiv \mathbf{v}' \wedge \mathbf{B}$ in the *S/C reference frame*, induced by the relative *S/C velocity* $\mathbf{v}'$ in the magnetized ambient plasma co-rotating with the planet. Capture is more effective the lower the incoming *S/C* periapsis because the planetary *dipole-field* $\mathbf{B}$ decreases as inverse cube of distance to the planet, so Lorentz drag decreases rapidly, as the inverse 6th power.

Also, since Lorentz-drag will peak at periapsis of a *S/C* orbiting a planet, it will have little effect on periapsis itself. In the 2-body general relation between specific energy ε and eccentricity e at constant periapsis r_p ,

$$\varepsilon = (e - 1) \mu / 2 r_p \quad (1)$$

any sequence of drag-work steps will directly relate e and ε . For a *S/C Hohmann-transfer* between heliocentric circular orbits at Earth and planet, the arriving velocity v_∞ of the hyperbolic orbit in the planetary frame provides an orbital specific energy $\varepsilon_h = (1/2)v_\infty^2$. Using v_∞ in (1) yields

$$e_h - 1 = v_\infty^2 R / \mu \quad (2)$$

where μ is the gravitational constant and we set periapsis $r_p \approx R$. A Jovian gravity-assist [8] can reduce eccentricity, along with v_∞ , to a value $e_h \approx 1.01$ [6], helping magnetic capture of a *S/C* into elliptical orbit.

Planetary capture, requiring negative Lorentz drag-work, $\dot{W}_d/M_{SC} = \Delta\varepsilon < 0$, allows writing

$$\frac{|\dot{W}_d|}{m_t} = \frac{|\dot{W}_d|}{M_{SC}} \times \frac{M_{SC}}{m_t} = |\Delta\varepsilon| \times \frac{M_{SC}}{m_t} \quad (3)$$

We will find $|\dot{W}_d|/m_t$ to be a function of just ambient conditions. Greater capture efficiency in (3) thus requiring lower $|\Delta\varepsilon|$, an optimum value corresponds to eccentricity after capture e_c being just below unity. This allows to calculate efficiency from drag work along the parabolic orbit at periapsis. Using (2) and (3), we finally find an expression for capture efficiency, depending on Lorentz drag work and the hyperbolic velocity v_∞ ,

$$\frac{|\dot{W}_d|}{m_t v_\infty^2 / 2} = \frac{M_{SC}}{m_t} \times \frac{e_h - e_c}{e_h - 1} \sim \frac{M_{SC}}{m_t} \quad (4)$$

We may calculate drag work using the radial speed rate in parabolic orbits to write

$$\int_{\Delta t} |\dot{W}_d| dt = 2 \times \int_{r_p}^{r_u} \frac{|\dot{W}_d| dr}{dr/dt} = 2 \int_{r_p}^{r_u} \frac{|\dot{W}_d| r dr}{\sqrt{2\mu(r - r_p)}} \quad (5)$$

with r_u a yet undefined upper limit. Next we calculate drag power

$$\dot{W}_d = \mathbf{v} \cdot [\mathbf{L}_t \mathbf{I}_{av} \wedge \mathbf{B}] = -\mathbf{L}_t \mathbf{I}_{av} \cdot (\mathbf{v} \wedge \mathbf{B}) \quad (6)$$

using length-averaged current I_{av} as bounded by the *short-circuit* value, $\sigma_t E_m \times h_t w_t$, with σ_t , h_t and w_t being tape-tether conductivity, thickness and width,

$$\mathbf{L}_t \mathbf{I}_{av} = \mathbf{L}_t \times i_{av} w_t h_t \sigma_t E_m \times \mathbf{u}_t, \quad i_{av}(L_t/L_\star) < 1 \quad (7)$$

$L_\star \propto (E_m/N_e^2)^{1/3}$ being certain characteristic ambient-plasma length, I_{av} only depending on electron density through i_{av} [9]. With the tether along the motional field $\mathbf{E}_m$, drag power in (6) becomes

$$\dot{W}_d = -i_{av} \sigma_t L_t w_t h_t \times (\mathbf{v}' \wedge \mathbf{B}) \cdot (\mathbf{v} \wedge \mathbf{B}) = -i_{av} \sigma_t \frac{m_t}{\rho_t} B^2 (\mathbf{v} \cdot \mathbf{v}') \quad (8)$$

and, using conservation of angular momentum, we write

$$\mathbf{v} \cdot \mathbf{v}' = \mathbf{v} \cdot (\mathbf{v} - \Omega r_p \mathbf{u}_\phi) = v^2 - \Omega r_p v_\phi \Rightarrow \quad (9)$$

$$r(\mathbf{v} \cdot \mathbf{v}') = r[v^2 - \Omega r_p v_\phi] = 2\mu \left[1 - r \Omega \frac{r_p}{2\mu} \sqrt{\frac{2\mu}{r_p}} \right] = 2\mu \left(1 - \frac{r}{r_M} \right) \quad (10)$$

$$r_M/r_p \equiv \sqrt{2} (a_S/r_p)^{3/2} \propto (\rho_{pl}/\Omega^2)^{1/2} \quad (11)$$

with r_M , where $\mathbf{v} \cdot \mathbf{v}'$ changes sign, being the maximum radius presenting drag, and $a_S = (\mu/\Omega^2)^{1/3}$ being the radius of an equatorial circular orbit where velocities of *S/C* and co-rotating plasma are equal, $(\mu/a_S)^{1/2} = \Omega a_S$. The last expression above applies in the present analysis, where $r_p \approx R$.

We shall use values at a_S as reference values, introducing the magnetic dipole law to write $B(r) = B_S a_S^3/r^3$, finally writing Eq. (4) as

$$|\dot{W}_d| / \frac{1}{2} m_t v_\infty^2 \equiv \tilde{B}_S^2 \times \tilde{W} \quad (12)$$

$$\tilde{B}_S^2 = \sigma_t B_S^2 a_S v_S / 2^{5/6} \rho_t v_\infty^2 \quad (13)$$

$$\tilde{W} = 2 < i_{av} > r \times \int_1^{r_M} \frac{(\tilde{r}_M - \tilde{r}) d\tilde{r}}{\tilde{r}^6 \sqrt{\tilde{r} - 1}}, \quad (\tilde{r} \equiv r/r_p) \quad (14)$$

As regards the above radial-average of the normalized length-average current i_{av} , consider the particularly simple regime for $L_t/L_\star > 4$

$$1 - i_{av} = \frac{L_\star}{L_t} \left[\alpha \frac{E_m^{1/3}}{L_t} \times \left(\frac{\sigma_t h_t}{N_e} \right)^{2/3} \right], \quad \frac{L_\star}{L_t} < \frac{1}{4} \quad (15)$$

yielding $i_{av} > 0.75$ [9]. If this regime applies at the lowest relevant N_e values, it should allow writing $< i_{av} > \approx 1$. However small plasma density N_e might reasonably be, it may be balanced by using a long enough tether. Note that this would favour using tethers for heavier *S/C*. Actually, a longer tether may keep the same mass by reducing width, condition for validity of the standard OML (*orbital motion limited*) regime on current collection by a tether, is keeping w_t below some upper bound, roughly 4 times *Plasma Debye length*.

Note now the very steep decrease away from periapsis in the radial rate of (14), as advanced,

$$1/\tilde{r}^6 \sqrt{\tilde{r} - 1}, \quad (16)$$

calculations of the integral not requiring to go far from $\tilde{r} = 1$. Independently, r_M places a definite limit to the range of integration. Which limitation is more effective, depends on the r_M value. For a large value, case of Neptune, as shown in Table 1, one can just ignore $\tilde{r}$ in the numerator inside the integral, altogether.

On the other hand, for a smaller R_M as in the case of Saturn, it pays

Table 1
Saturn/Neptune comparison.

	Saturn	Neptune
ρ_{pl} (gr/cm ³)	0.6871	1.638
Period (hours)	10.656	16.11
Drag reach r_M (in parabolic orbit)	3.7 R_S	8.9 R_N
Dipole Tilt	<0.5°	47°
Dipole Offset	0.06 R_S	0.55 R_N

Fig. 1. Position of the magnetic dipole and approximate SC trajectory.

to eliminate its limiting character by moving from *prograde* to *retrograde* orbiting, just writing $r_M + r$ in that numerator, with a gain in the integral (and in capture efficiency) of about 2. The integral converges very rapidly, increasing from 0.971 $\hat{r}_M$ to just 1.008 $\hat{r}_M$, if taking the upper limit from 1.5 to 2 [6]. In the present work we will go back to prograde capture, the drop by half in capture efficiency not being determinant here; our goal is allowing slow flybys exploration of moon Enceladus. Table 1 clearly shows that Saturn and Neptune present opposite cases among the Outer Giant Planets as regards density and spin, as emerging from the last expression in (11), resulting in opposite extremes in radial reach of Lorentz drag, $3.7 R_S$ as against $8.9 R_N$.

Another basic difference among Outer Giants arises from the magnetic structure of the field B. A planetary magnetic field is due to a system of stationary currents in small volumes inside, as described by its magnetic moment and dipole law. The Saturn dipole is located at its center and parallel to the rotation axis; this holds approximately for Jupiter, too. On the other hand, the Neptune dipole is highly tilted and offset. For Neptune capture, efficiency depends on the longitude at periapsis; Fig. 1 shows the optimum case, with the S/C facing the dipole when reaching periapsis, with minimum distance ρ to the dipole. Lorentz drag decreasing with the inverse 6th power of ρ , faster convergence in the capture work integral allows not to go beyond about $1.12 r_p$ [10], as against $1.5 r_p$ for Saturn. Both basic differences between extreme Saturn and Neptune cases, suggest that joint tether missions to different planetary systems of moons might not be effective.

There is a further condition that separates Neptune of the other 3 Outer Giants. It has just 1 large moon, Triton, which is in retrograde orbit. Although unnecessary for greater capture efficiency because of the large $8.9 R_N$ value, visiting that moon will certainly need retrograde capture. Along with the final Outer planet, Uranus, having its rotation axis nearly lying in the ecliptic plane, both singular differences might be signs of collisions with other big bodies in the intriguing, early Solar System dynamics.

2.1. Moon/spacecraft resonances

Following capture, the S/C apoapsis can be lowered, at given periapsis, to a circular moon orbit, allowing for a 1:2 resonance with the S/C elliptical orbit if the moon orbital radius satisfies certain condition. This would allow conveniently slow, tangential S/C flybys of the moon, with two periapsis passes for each flyby. In the present problem the periapsis value was fixed, $r_p \approx R$, to make capture efficient, as we argued at length above. We have just found that moon Enceladus does satisfy the condition for that 1:2 resonance:

The period of a moon circular orbit of radius r_m , around a planet with gravitational constant μ , is $\tau_m = 2\pi r_m^{3/2}/\sqrt{\mu}$. The period of an elliptical orbit with given periapsis r_p , and apoapsis at r_m , eccentricity being $e_{SC} = (r_m - r_p)/(r_m + r_p)$, is

$$\tau_{SC} = \frac{2\pi}{\sqrt{\mu}} \left(\frac{r_p}{1 - e_{SC}} \right)^{3/2} = \frac{2\pi}{\sqrt{\mu}} \left(\frac{r_m}{1 + e_{SC}} \right)^{3/2} \quad (17)$$

Condition for 1:2 resonance being $\tau_m = 2\tau_{SC}$, there results $e_{SC} = 4^{1/3} - 1 \approx 0.59$, and

$$\frac{r_p}{r_m} (\approx 0.2597) = 2^{1/3} - 1 (\approx 0.2599) \quad (18)$$

where we used values $r_m = r_{Enc} \approx 238000$ km, and $r_p \approx R_S + \text{capture} - \text{periapsis altitude} \approx 60300$ km + 1500 km for some representative altitude, affecting little the r_p/r_m ratio.

Certainly, the 1:2 resonance does not apply to moon Dione, for which we will use non-tangential flybys at 1:1 resonance, with one periapsis pass per flyby. Now we will have $\tau_{SC} = \tau_D$, i.e.,

$$\frac{2\pi}{\sqrt{\mu}} \left(\frac{r_p}{1 - e_{SC}} \right)^{3/2} = \frac{2\pi}{\sqrt{\mu}} r_D^{3/2} \quad (19)$$

yielding $1 - e_{SC} = r_p/r_D \approx 0.160$, having used $r_D \approx 377400$ km and $r_p \approx R_S$. We thus find $e_{SC} \approx 0.840$, with the apoapsis of the orbit at 1:1 resonance with Dione, $r_a = (1 + e_{SC}) \times r_D \approx 694400$ km, lying between moons Rhea and Titan. Note that 1 revolution period of moon Dione (2.74 days) does correspond to 1 periapsis pass of the S/C during Dione flybys, whereas it corresponds to 4 S/C periapsis passes (0.685 days) during the Enceladus flybys, when Dione, Enceladus, and the spacecraft are in 1:2:4 resonance.

Apoapsis lowering will occur at successive periapsis passes, resulting in a series of elliptical orbits with common periapsis and decreasing eccentricities, with changes in periapsis position being small second-order effects. As noticed in the following section, eccentricity decrements being small, about 0.02 say, like at capture itself, calculations may be carried out as if eccentricity, though different from unity, was kept constant during each perijove pass. Changes in calculation, as compared with the capture analysis, are using the energy equation for each particular eccentricity value,

$$v^2 = \mu \left(\frac{2}{r} - \frac{1 - e}{r_p} \right) \quad (20)$$

instead of $v^2 = 2\mu/r$, while using the radial speed rate dr/dt value resulting from (20) and the angular-momentum conservation law,

$$r^2 d\theta/dt = r_p v_{pe}. \quad (21)$$

We then have

$$\left(\frac{dr}{dt} \right)^2 = v^2 - \left(r \frac{d\theta}{dt} \right)^2 = \mu \left(\frac{2}{r} - \frac{1 - e}{r_p} \right) - \frac{(1 + e)\mu r_p}{r^2} \quad (22)$$

where we used the periapsis velocity $v_{pe} = [\mu(1 + e)/r_p]^{1/2}$. Radial speed-rate vanishing, in (22) above, occurs at 2 values of radius, periapsis r_p and apoapsis $r_a = r_p(1 + e)/(1 - e)$, finally yielding

$$\frac{dr}{dt} = \sqrt{(1 + e)\mu(r - r_p)[1 - (r/r_a)]/r} \quad (23)$$

replacing the radial rate at $e = 1$, when the apoapsis radius $r_a = r_p(1 + e)/(1 - e)$ was at infinity.

Next, use (20) in Eq. (9), and write

$$\begin{aligned} r \mathbf{v} \cdot \mathbf{v}' &= r \left[\mu \left(\frac{2}{r} - \frac{1 - e}{r_p} \right) \right] - r \Omega r_p v_{pe} = 2 \\ &\mu \left[1 - \frac{r(1 - e)}{r_p} - r \frac{\Omega r_p}{2\mu} \sqrt{\frac{\mu(1 + e)}{r_p}} \right] \\ r \mathbf{v} \cdot \mathbf{v}' &= 2\mu \left[1 - r \left(\frac{1 - e}{2r_p} + \sqrt{\frac{1 + e}{2}} \frac{1}{r_M} \right) \right] \end{aligned} \quad (24)$$

replacing $2\mu[1 - (r/r_M)]$, from Eq. (10), for $e = 1$.

3. A Dione-Enceladus tour scheme

Using the above results for arbitrary eccentricity e , yields $|W_{de}|/(m_t v_{\infty}^2/2) = \tilde{B}_S^2 \tilde{W}_e$

Table 2Values of the function $f(\tilde{r}, \tilde{r}_M, e)$ (Eq. (26)).

$\tilde{r}$	$e = 1$	$e = 0.84$ (Differences)	$e = 0.59$ (Differences)
1	2.70	2.66 (1.5%)	2.67 (1.1%)
1.25	2.45	2.35 (4.3%)	2.23 (9.9%)
1.50	2.20	2.03 (8.4%)	1.75 (25.7%)

$$\tilde{W}_e = 2 < i_{av} > \tilde{r}_M^{8/3} \int_1^{\tilde{r}_u} \frac{d\tilde{r}}{\tilde{r}^6 \sqrt{\tilde{r} - 1}} \times f(\tilde{r}, \tilde{r}_M, e) \quad (25)$$

$$f(\tilde{r}, \tilde{r}_M, e) = \frac{\tilde{r}_M - \tilde{r}[\sqrt{(1+e)/2} + \tilde{r}_M(1-e)/2]}{\sqrt{[(1+e) - (1-e)\tilde{r}]/2}} \quad (26)$$

which recovers Eq. (14) for $e = 1$. Both $\tilde{r}_M$ and $\tilde{B}_S^2$ are as for $e = 1$.

As e is decreased from 1, the upper limit in the integral keeps being the r -value for vanishing numerator in the second ratio above, until a value $e \approx 0.28$ is reached, with denominator vanishing too. At lower e , the upper limit in the integral is the apoapsis radius, at vanishing denominator. Note that this change in behavior occurs well below the $0.84 < e < 1$ range involved in reaching resonance with Dione and its flybys exploration, and below the $0.59 < e < 0.84$ range required for the Enceladus flybys.

An approximate, extremely simplified analysis is here discussed. For the eccentricity ranges of interest, $0.84 < e < 1$ and $0.59 < e < 0.84$, and the radial range of integration, $1 < r/r_p < 1.5$, Table 2 suggests that the functional factor $f(\tilde{r}, \tilde{r}_M, e)$ in Eqs. 25 and 26 might be reasonably approximated throughout by using its $e = 1$ values, with (25,26) just replaced by (14). The error would appear substantial, however, near the radial end, at the lower eccentricity. Let us recall, however, the very steep decrease away from periapsis, in the radial rate, given by (16), at both Eqs. (14) and (25), making values near $r = 1.5r_p$ contribute little to integrals involving that rate, as noticed in the paragraph following Eq. (16). Results from the simplified analysis might reasonably apply for the $0.59 < e < 1$ tour.

3.1. Moon tour

With Eq. (14) replacing (25,26) in the above simplified analysis, S/C -orbit evolution can be described in terms of number of successive periapsis passes. For M_{SC}/m_i such that e_c is about 0.99, it would take 7 steps following capture, for the S/C to reach $e = 0.85$, with the capture value $\Delta e \approx 0.02$. A last eccentricity decrement must be reached in two convenient steps by switching the current off appropriately over part of the drag arc to allow for a first flyby of Dione while reducing Δe by half. Switching off the current afterward over the entire resonance orbit would allow for repeated flybys, with the moon overtaking each time the S/C . It would later take 13 steps to reach Enceladus at $e = 0.59$ from Dione at $e = 0.84$.

3.2. Power generation

A large amount of energy could be taken from the orbital motion of the S/C during capture and during each one of the successive periapsis passes, into the tether electric circuit. A fraction taken by electric loads at the cathodic end, could have a weak effect on tether current and the related tether dynamics. A part of that energy could be used during each of the operation steps, with the rest saved/stored in batteries, for later use. Operation would keep emphasis on reserving power for use at the planned steps at Enceladus, main objective of the mission, as regards life search.

The revolution period of Dione is about 2.74 days. The S/C at resonance 1:1 would take 13.70 days in making, say, 5 flybys. The S/C at resonance 1:2 would take 1 flyby per period of Enceladus, or 13.70 days in making 10 flybys.

3.3. Minor issues

Radiation is a big issue for tethers at Jupiter but not at Saturn, which lacks strong radiation belts. As regards tether dynamic instabilities, they are generally quite slow [11], while the times involved in the mission are short. Regarding the J_2 zonal harmonic coefficient, which is 15 times as large as Earth's, and comparable to Jupiter, it requires a minor correction involving apsidal precession, the way it was made for Jupiter [5], to consider in planning an Enceladus-Dione mission.

4. Summary of results

Saturn moon *Enceladus* stands out, along with Jovian moon *Europa*, as particular *moon of interest* in the search for conditions of habitability, in parallel to search for life, in the *ice moons* of the *Outer Giant Planets*. Moons Enceladus and *Dione* are in 1:2 resonance in the Saturn system. The very recent discovery (fall of 2018), as result of mission Cassini, of intriguing *linear virgae* at *Dione*, makes exploring both moons a convenience. We have presented a tether-mission concept making possible multiple flybys of both moons, though Enceladus would be of most critical interest. We have proved that a SC orbit at Saturn with periapsis very near planet radius as required by a tether, and apoapsis at Enceladus orbit satisfies the condition for a 1:2 moon/SC resonance, allowing conveniently slow, parallel SC flybys of the moon. Our analysis shows that following magnetic capture by the SC-tether, repeated free Lorentz-drag, keeping periapsis near constant, could take the SC apoapsis down to Enceladus.

Acknowledgements

This work was supported by MINECO/AEI, under Project ESP2017-87271-P, and FEDER/EU.

References

- [1] J.R. Spencer, F. Nimmo, Enceladus: an active ice world in the Saturn system, *Annu. Rev. Earth Planet Sci.* 41 (2013) 693–717, <https://doi.org/10.1146/annurev-earth-050212-124025>.
- [2] H.-W. Hsu, F. Postberg, Y. Sekine, T. Shibuya, S. Kempf, M. Horányi, A. Juhász, N. Altobelli, K. Suzuki, Y. Masaki, et al., Ongoing hydrothermal activities within Enceladus, *Nature* 519 (7542) (2015) 207–210, <https://doi.org/10.1038/nature14262>.
- [3] J.H. Waite, C.R. Glein, R.S. Perryman, B.D. Teolis, B.A. Magee, G. Miller, J. Grimes, M.E. Perry, K.E. Miller, A. Bouquet, et al., Cassini finds molecular hydrogen in the Enceladus plume: evidence for hydrothermal processes, *Science* 356 (6334) (2017) 155–159, <https://doi.org/10.1126/science.1257033>.
- [4] E.S. Martin, D.A. Patthoff, Mysterious linear features across Saturn's moon Dione, *Geophys. Res. Lett.* 45 (20) (2018) 10–978, <https://doi.org/10.1029/2018gl079819>.
- [5] J.R. Sanmartín, M. Charro, E.C. Lorenzini, H. Garrett, C. Bombardelli, C. Bramanti, Electrodynamic tether at Jupiter - II: fast moon tour after capture, *IEEE Trans. Plasma Sci.* 37 (4) (2009) 620–626, <https://doi.org/10.1109/tps.2009.2013955>.
- [6] J.R. Sanmartín, J. Peláez, I. Carrera-Calvo, Comparative Saturn-versus-Jupiter tether operation, *J. Geophys. Res.: Space Physics* 123 (7) (2018) 6026–6030, <https://doi.org/10.1029/2018ja025574>.
- [7] J.R. Sanmartín, M. Charro, H.B. Garrett, G. Sánchez-Arriaga, A. Sánchez-Torres, Analysis of tether-mission concept for multiple flybys of moon Europa, *J. Propuls. Power* 33 (2) (2017) 338–342, <https://doi.org/10.2514/1.B36205>.
- [8] R. Battin, *An Introduction to the Mathematics and Methods of Astrodynamics*, Revised Edition, AIAA, AIAA education series, Reston, VA, 1999.
- [9] J.R. Sanmartín, M. Charro, E.C. Lorenzini, H. Garrett, C. Bombardelli, C. Bramanti, Electrodynamic tether at Jupiter - I: capture operation and constraints, *IEEE Trans. Plasma Sci.* 36 (5) (2008) 2450–2458, <https://doi.org/10.1109/TPS.2008.2002580>.
- [10] J.R. Sanmartín, J. Peláez, Tether capture of spacecraft at Neptune, *Acta Astronaut. (SI:Tethers in Space 2019)* (2020) Submitted for publication.
- [11] J. Peláez, E. Lorenzini, O. Lopez-Rebolal, M. Ruiz, A new kind of dynamic instability in electrodynamic tethers, *J. Astronaut. Sci.* 48 (2000) 449–476, <https://doi.org/10.2514/1.6473>.