ELECTRODYNAMIC TETHER AT JUPITER. 2. TOUR MISSIONS AFTER CAPTURE

J.R. Sanmartin (1), M. Charro (1), E.C. Lorenzini (2), H.B. Garrett (3),
C. Bramanti (4), and C. Bombardelli (4)

(1) *Universidad Politecnica de Madrid*, (2) *Università di Padova*,
(3) *Jet Propulsion Laboratory-NASA*, (4) *European Space Agency-ESTEC*

ABSTRACT

Three separate scenarios of an electrodynamic tether mission at Jupiter following capture of a spacecraft (SC) into an equatorial, highly elliptical orbit around the planet, with perijove at about 1.5 times the Jovian radius, are discussed. Repeated application of Lorentz drag on the spinning tether, at the perijove vicinity, can progressively lower the apojove. One mission involves the tethered-SC rapidly and frequently visiting Galilean moons; elliptical orbits with apojove down at the Ganymede, Europa, and Io orbits are in 2:5, 4:9, and 1:2 resonances with the respective moons. About 20 slow flybys of Io would take place before the accumulated radiation dose exceeds 3 Mrad (Si) at 10 mm *Al* shield thickness, with a total duration of 5 months after capture (4 months for lowering the apojove to Io and one month for the flybys). The respective number of flybys for Ganymede would be 10 with a total duration of about 9 months. An alternative mission would have the SC acquire a low circular orbit around Jupiter, below the radiation belts, and manoeuvre to get an optimal altitude, with no major radiation effects, in less than 5 months after capture. In a third mission, repeated thrusting at the apojove vicinity, once down at the Io torus, would raise the perijove itself to the torus to acquire a low circular orbit around Io in about 4 months, for a total of 8 months after capture; this corresponds, however, to over 100 apojove passes with an accumulated dose, of about 8.5 Mrad (Si), that poses a critical issue.

1 - INTRODUCTION

A full study of the giant, complex Jovian system is a central goal in planetary science. Particularly desired are missions to get a spacecraft (SC) into low orbits around moons *Europa* and *Io*, and *Jupiter* itself. Basic issues made manifest in the *Galileo* mission involve power and propulsion needs, trip times, and harsh radiation environment. A succesion of proposals for Jovian missions have followed each other: *Europa Orbiter*, *Jovian Icy Moons Orbiter* within *Project Prometheus*, *JUNO*, *Europa Geophysical Explorer*, *Io Jovicentric Orbiter*, *Ganymede Exploration Orbiter*, *Jovian Minisat Explorer*, … Proposals have moved from RTG´s to nuclear reactors, or back to solar arrays, for power; from chemical propulsion to high specific-impulse electrical thrusters with a variety of powering sources, for propulsion. Gravity assists have been considered for moon tours, while direct rather than gravity-assisted trips to Jupiter, as in the protracted Galileo mission, have been also considered. Whereas Galileo was designed for 0.15 Mrad Si radiation dose and accumulated 0.7 Mrad Si at end of its extended mission, dose values up to 3 Mrad Si have been contemplated.

The approach here discussed involves an electrodynamic (ED) tether to tap Jupiter's rotational energy for both power and propulsion. The positions of perijove and apojove in equatorial elliptical orbits, relative to the stationary (circular/equatorial) orbit at radius a_s, which lies at an energy maximum in the orbit/planet-spin interaction, would be exploited to conveniently make the induced Lorentz force to be drag or thrust, while generating power and navigating the system. A tether provides a mechanism to dissipate energy. The transformation

$$\bar{E}(\textit{tether frame}) - \bar{E}(\textit{plasma frame}) = \bar{E}_m \equiv (\bar{v} - \bar{v}_{pl}) \wedge \bar{B}$$

where $\bar{v}$, $\bar{v}_{pl}$ are velocities of S/C and local corotating plasma, with the electric field outside the tether negligible in the frame moving with the plasma, shows an outside field $\bar{E}_m$ in the tether frame that will drive a current $\bar{I}$ inside the tether with $\bar{I} \cdot \bar{E}_m > 0$. Using the Lorentz force $L\bar{I} \wedge \bar{B}$ on a tether of length L, Newton´s 3rd law for magnetic forces between steady-current systems proves there is a net power loss in the tether-plasma interaction,

$$L\bar{I} \wedge \bar{B} \cdot (\bar{v} - \bar{v}_{pl}) = -\bar{I} \cdot \bar{E}_m L < 0\,,$$

which is power appearing in the tether circuit. The Lorentz force would be thrust if $\bar{v}$ is opposite $\bar{v} - \bar{v}_{pl}$, which is the case for prograde, radius $a > a_s$ circular orbits [1].

ED-tether operation requires effective contact with the ambient plasma. State-of-art hollow cathodes are effective cathodic contactors. The problem of anodic contact with a highly rarefied plasma was solved in 1992, when it was proposed that, instead of using a big end-collector, the tether be left bare of insulation to allow it to collect electrons over the segment coming out polarized positive, as a giant cylindrical Langmuir probe in the orbital-motion-limited (OML) regime. Collection is efficient if the cross-section dimension is thin, the collecting area still being large because the anodic segment may be tens of kilometers long. A thin tape collects the same OML-current as a round wire of equal cross-section perimeter and will be much lighter; the optimal tether thus presents three disparate dimensions, $L >> w$ (*tape width*) $>> h$ (*tape thickness*).

The Jovian system is particularly appropriate for thrusting as well as dragging by an ED-tether with no external power. Operation requires plasma beyond the radius a_s to be *i*) dense enough, and *ii*) corotating with the planet. Jupiter has both low density and rapid rotation; as a result its stationary orbit lies at 1/3 the relative distance for Earth ($a_s \approx 2.24\ R_J$). Further, magnetic stresses at the surface are 100 times greater at Jupiter than at Earth, the Jovian plasmasphere reaching to about 3.8 R_J. Also, moon Io is at 1:2 *Laplace* resonance with Europa and 10 times relatively closer to its planet than the *Moon* is to Earth. Extreme tectonics and volcanism from tidal deformations inside Io make it to continuosly eject gas that is ionized and accelerated in the magnetosphere, and made to corotate as a giant plasma torus denser than the plasmasphere, reaching to Europa at 9.38 R_J.

Tether drag/thrust would only be effective within either plasmasphere or torus, with tether current shut off at convenience. Also, the tether could serve as power source whenever an electric load is plugged in. A large energy could be tapped (used locally or saved for later) from the giant power developed during S/C capture and other high-current operations with negligible effect on its dynamics; current could also be switched on away from such operations to just generate power.

The apojove could be lowered following capture through a sequence of perijove passes, allowing frequent flybys of Galilean moons, or lowered all the way down to reach a low circular orbit around Jupiter (Fig.1). Also, with the apojove in the fast-flowing plasma torus, or further down in the outer region of the plasmasphere, switching the tether current off around perijove and on around apojove would produce a sequence of orbits with increasingly higher perijove, to finally carry the S/C deep in the torus, allowing capture by Io [2].

2 - CAPTURE BY A FAST ROTATING TETHER IN PARABOLIC ORBIT

S/C capture is doubly critical for a tether as compared with a mass-consuming thruster, which faces a separate issue in attaining closed-orbit evolution. In the tether case, closed orbits could evolve, after capture, under repeated Lorentz force. Tether performance depends on ambient conditions ($\bar{E}_m$, $\bar{B}$, and electron plasma density N_e) as well as on the orbit geometry, assumed equatorial. Capture, discussed in detail elsewhere [3], is just sketched here.

The Jovian region of interest here lies in the so called inner magnetosphere, where the field B is dominantly produced by currents inside Jupiter, limited measurements determining dominant terms in a multipole expansion. A simple no-tilt, no-offset dipole model will do in our analysis. We shall use the *Divine-Garrett* model of the thermal Jovian plasma, basically constructed from *Pioneer* 10, 11 and Voyager 1, 2 *in situ* data, supplemented by Earth-based observations of synchrotron emission. Torus and plasmasphere, which has spherical symmetry, are modelled separately; only the plasma density profile, which has a simple analytical representation, is involved in the calculations.

S/C capture requires drag to make a minimum work $|W_C|$ to take the orbital energy from a positive value $M_{S/C}\, v_\infty^2/2$ in the incoming hyperbolic orbit to some negative value. The greater is that work, the lower are apojove radius and eccentricity, e_1, in the first orbit following capture. A calculation of $|W_C|$ must take into account that the S/C will follow an orbit far from circular during capture. This involves considering ambient conditions that vary along the orbit; a motional field that has a complex behaviour (the strict condition $r < a_s$ for Lorentz drag not strictly applying for elliptical orbits); and a tether oriented neither normal to the trajectory nor along the local vertical. Actually, the weak gravity gradient in Jupiter requires setting the tether to spin.

Fortunately the incoming orbit starts barely hyperbolic and will end barely elliptic. With the Lorentz force only acting around perijove, the energy per unit mass of the incoming hyperbolic orbit and following elliptical orbits depends just on eccentricity,

$$\varepsilon = \frac{-\mu_J}{2r_p}(1-e)\,. \tag{1}$$

For $\varepsilon_h = ½\, v_\infty^2$ the hyperbolic eccentricity will be just above unity,

$$e_h - 1 = \frac{v_\infty^2 r_p}{\mu_J} \equiv \tilde{v}_\infty^2 \frac{r_p}{R_J}\,, \tag{2}$$

where μ_J is Jupiter's gravitational parameter and $\tilde{v}_\infty^2 \approx 0.018$ for $v_\infty \approx 5.64$ km/s (case of Hohmann transfer). We make the ansatz that the S/C is barely captured, with e_1 just below unity,

$$\frac{-W_c}{M_{SC}v_\infty^2/2} = \frac{-\Delta\varepsilon}{v_\infty^2/2} = \frac{e_h - e_1}{e_h - 1} = O(1)\,. \qquad (3)$$

This means that the orbit is hardly affected locally, and that we can ignore all changes except the dramatic faraway effect of having it changed from open to closed. We will consider throughout capture a parabolic (e = 1) orbit, which is entirely determined by its perijove radius r_p.

With the Jovian, no-tilt magnetic field ($-B\bar{k}$, $B > 0$) pointing south at the equator, and taking an unit vector $\bar{u}$ along the tether, from the cathodic to the anodic end (the direction of conventional current), Lorentz force and corresponding mechanical power read (Fig. 2a)

$$\bar{F} = L\bar{I}_{av} \wedge \bar{B} = L\,B\,I_{av}\,(\bar{k} \wedge \bar{u})\,, \qquad (4)$$

$$\dot{W} = \bar{F} \cdot \bar{u}_t v = vL\,B\,I_{av}\,\bar{k} \cdot (\bar{u} \wedge \bar{u}_t) = -vLBI_{av} \sin(\alpha_E + \varphi) \qquad (5)$$

The length-averaged current I_{av} in (5) will depend on impedances in the tether circuit. The hollow cathode has negligible contact impedance; we shall also neglect both the radiation impedance for current closure in the Jovian plasma (indeed negligible in Low Earth Orbit) and any power-output impedance, assumed low.

If the ohmic tether resistance were negligible too, bare-tether analysis shows the tether to be biased positive throughout its length, and the average current to be 2/5 of the OML current collected by the tether if at uniform bias E_mL, where E_m is the projection of $\bar{E}_m$ along the tape,

$$I_{av}(OML) \equiv I_{OML} = \frac{2}{5}\,\frac{2w\,L}{\pi}\,eN_e\sqrt{\frac{2eE_mL}{m_e}}\,. \qquad (6)$$

Ohmic effects limit the maximum current the tape can carry to the short-circuit value,

$$I_{av}\,(short\ circuit) \equiv I_{shc} = \sigma_c\, wh\, E_m, \qquad (7)$$

with σ_c the tether conductivity. In general we will have

$$I_{av} / I_{shc} = i_{av}(I_{OML} / I_{shc}) \qquad (8)$$

The electron current I in a bare tether starts from zero at the anodic end A and increases with distance s, as collected electrons pile up over the segment biased positive with respect to the local plasma (Fig. 2b). Tether bias decreases with s at decreasing rate, which vanishes where, and if, the current reaches the short-circuit value, i_{av} = 1. Also, since bias must be negative at the cathodic end C to allow electron ejection by the hollow cathode, there exists a segment BC at negative bias, with negligible ion collection. We omit here the bare-tether analysis of current and bias profiles that determines the dependence of i_{av} on the ratio I_{OML}/I_{shc}. It will suffice here to observe the relation

$$I_{OML} / I_{shc} \equiv 0.3\,(L / L^*)^{3/2} \propto L^{3/2} N_e / \sigma_c h \sqrt{E_m} \qquad (9)$$

where L^* as defined above is a length usually introduced to describe bare-tether profiles.

In Fig. 2a we have

$$\bar{E}_m = \bar{v}' \wedge \bar{B} = \bar{u}_E v'B\,, \qquad E_m \equiv \bar{E}_m \cdot \bar{u} = v'\,B\cos\varphi > 0, \qquad (10a, b)$$

where $\bar{v}' \equiv \bar{v} - \bar{v}_{pl}$. Using Eqs. (9) and (10b), the average current in (8) can be written as

$$I_{av} = i_{av}\, \sigma_c wh\, v'\, B \cos\varphi, \qquad (11)$$

the ratio I_{OML} / I_{shc}, and thus i_{av}, being itself a function of $cos\varphi$. Averaging in Eq. (5) over the angle φ at fixed r, and using $\bar{v}' \perp \bar{u}_E$ in Fig. 2a to write $v'\sin\alpha_E = v_t'$, we find

$$< \dot{W} > \; = \; -\sigma_c\, Lwh\, B^2\, vv'_t < i_{av} \cos^2\varphi >. \qquad (12)$$

Finally, integrating over the time on the full drag arc, we obtain

$$W_C = \int < \dot{W} > dt = -2\sigma_c Lwh \int_{r_p}^{r_M} \frac{B^2 v^2\, rdr}{v_s\sqrt{a_s (r - r_p)}} \left(1 - \frac{r}{r_M}\right) < i_{av} \cos^2\varphi > \qquad (13)$$

where we used $v_t' = v\,(1 - r/r_M)$ as following for the parabolic orbit, drag vanishing with v_t' at the radius

$$r_M(r_p) \equiv a_s \sqrt{2a_s / r_p}\,. \qquad (14)$$

Using $B = B_s a_s^3 / r^3$, $v^2 = v_s^2\, a_s / r$ ($B_s \approx 0.38$ gauss, $v_s \approx 39.8$ km/s), we finally find

$$\frac{-2W_C}{m_t v_\infty^2} = \frac{e_h - e_1}{e_h - 1}\,\frac{M_{SC}}{m_t} = \tilde{B}_s^2\; S\!\left(\frac{r_p}{R_J}, \frac{\hat{\lambda}}{\tilde{B}_s^{4/3}}\right), \qquad (15)$$

$$\hat{\lambda}^{3/2} \equiv \frac{10}{3}\, \frac{\sqrt{v_s}\,(eB_s L / m_e)^{3/2}}{v_\infty^2}\, \frac{a_s m_e N_s}{h\,\rho_t}. \qquad (16)$$

$$\tilde{B}_s^2 \equiv \frac{\sigma_c B_s^2\, a_s v_s}{2^{5/6}\, \rho_t v_\infty^2}, \qquad \frac{\hat{\lambda}}{\tilde{B}_s^{4/3}} \propto \frac{L}{(h\sigma_c)^{4/3}}. \qquad (17a, b)$$

In case of aluminum tape and Hohmann transfer we have

$$\tilde{B}_s^2 \approx 2.11, \qquad \hat{\lambda} \approx \frac{L}{80km}\left(\frac{0.05mm}{h}\right)^{2/3}. \qquad (18a, b)$$

The limit $\hat{\lambda} / \tilde{B}_s^{4/3} \to \infty$ corresponds to dominant ohmic effects, leading to $i_{av} \to 1$; a small value of that ratio corresponds to negligible ohmic effects. Figure 3 represents the right-hand side of Eq. (15), which is the S/C-to-tether mass ratio in case $1 - e_1 = 0^+$. We note that $\tilde{B}_s$ is about 20 times smaller for Saturn than for Jupiter. This will make tether capture in Saturn very difficult.

3 - LOWERING THE APOJOVE

We here consider two types of missions, which are made possible by repeated application of the Lorentz force after capture, keeping r_p. One type involves apojove lowering as suggested in Fig.1. We consider two missions of this type: *i*) Frequent flybys of Galilean moons at resonance orbits, with perijoves around 1.5 R_J, and *ii*) acquiring a low circular orbit around Jupiter. The other type of mission involves perijove raising, as also suggested in Fig.1. One such mission is *iii*) acquiring a low circular orbit around moon Io, to be discussed in Sec. 6.

As regards apojove lowering, if current is on along the drag arc as the spacecraft returns to the perijove neighborhood, the apojove radius r_a will be reduced. Further reductions will occur at successive perijove passes, resulting in a series of elliptical orbits with common perijove and decreasing eccentricities (changes in the perijove position are small, second-order effects). We can then make the apojove distance r_a meet the orbital radius of any Galilean moon. As with the capture analysis, calculations are carried out as if eccentricity, though different from unity, was kept constant during each successive pass.

As we shall now see, the drag work per perijove pass $W_{e/d}$ is nearly independent of the value of eccentricity except for low values. The eccentricity decrement per pass,

$$\Delta e = 2r_p \,\Delta\varepsilon / \mu_J , \qquad (19)$$

as following from Eq. (1), is itself nearly independent of e, making for a simple discussion of orbit evolution. An increase of Δe is found to occur for low enough apojove and eccentricity, when drag acts throughout the entire orbit, from apojove to perijove and back.

A calculation of $W_{e/d}$, though more involved, follows the lines of the previous calculation of W_C. We finally find

$$\frac{-2W_{e/d}}{m_t v_\infty^2} = \tilde{B}_s^2 S_e\left(\frac{r_p}{R_J}, \frac{\hat{\lambda}}{\tilde{B}_s^{4/3}}, e\right) \qquad (20)$$

Figure 4 shows S_e versus e for a perijove radius 1.3 R_J and several $\hat{\lambda}$ values. S_e is indeed nearly independent of eccentricity ($S_e \approx S$ or $W_{e/d} \approx W_C$) except at small e. We find that drag acts over the entire orbit for r_a < 2.05 R_J, or e < 0.22, which falls in the eccentricity range showing a rapid increase of S_e in Fig. 4. For r_p = 1.1 R_J and r_p = 1.5 R_J, we find full orbit drag for e < 0.29 (r_a < 2.0 R_J), and e < 0.17 (r_a < 2.1 R_J), respectively.

We can now readily describe orbit evolution in terms of the number of successive perijove passes. Consider, for simplicity, conditions leading to $e_h \approx 1.02$, $e_1 \approx 0.98$ and $\Delta e \approx - 0.04$ at not too small e. A series of passes at fixed perijove, with repeated small decrements in eccentricity, would lead to a sequence of e values, 0.98, 0.94, 0.90, 0.86, 0.82, 0.78, 0.74, 0.70, 0.66, 0.62,... The orbital period of the SC after each perijove pass is $\tau_{orb} \propto [\, r_p / (1 - e)]^{3/2}$, yielding a corresponding sequence of periods in days, 80.3, 15.4, 7.2, 4.3, 3.0, 2.2, 1.7, 1.4, 1.1, 0.97, …

4 - MOON-FLYBYS / LOW JOVIAN ORBIT MISSIONS

Following the first orbit after capture, the tethered-spacecraft apojove could be made to rapidly reach the orbits of the Galilean satellites. Note that elliptical orbits with apojoves at the orbits of Io, Europa and Ganymede, would be at resonances 2:1, 9:4, and 5:2 with the respective moons at perijoves near $r_p \approx 1.5$ R_J in all three cases. Drag fine-tuning at perijove passes by switching hollow cathodes and current appropriately, would result in a first flyby of any of those moons.

Switching off the current afterwards over the entire corresponding orbit would allow repeated flybys, with the moon overtaking, each time, the slower moving SC.

Consider the moon Ganymede, its orbital radius being about 15.0 R_J. The eccentricity of an elliptical orbit with perijove at 1.5 R_J and apojove at 15.0 R_J is $e \approx 0.82$. For the small $\Delta e = -0.04$ decrement mentioned above, the SC could reach that eccentricity with four passes following capture. The time invested in reaching that first apojove flyby, from the perijove capture pass would be a total of about 109 days. Each following flyby would require 5 SC orbits, and a time lapse that is twice the Ganymede orbital period, or 8 times Io´s period, i.e., 8 × 1.77 days = 14.2 days.

The orbital radius of Io is about 5.9 R_J, the corresponding SC-orbit eccentricity for perijove at 1.5 R_J being 0.59. It could be reached in ten current-on perijove passes following capture, the total time to that first apojove flyby being 118 days. Each additional flyby would require 2 SC orbits, and a time lapse that is the Io orbital period of 1.77 days. In turn, the orbital radius of moon Europa is 9.4 R_J, the corresponding SC-orbit eccentricity being 0.72. It could be reached in seven perijove passes following capture. Each flyby would require 9 SC orbits, and a time lapse that is four times the Europa orbital period, i.e. again 8 times Io´s period, or 14.2 days.

The extremely frequent access of the tethered SC to the orbits of Galilean moons is to be compared to the frequency of visits in the *Galileo* mission. Galileo made 34 close encounters or flybys in almost 8 years. It thus took nearly three months on the average from one visit to the next. Notice, however, that the tethered SC would orbit through the intense radiation belts near Jupiter on each visit to a moon; radiation dose calculations are discussed in the next section.

To reduce the number of orbits (and the radiation dose) required to get the SC apojove to the orbit of any of those moons, prior to a sequence of visits, the eccentricity jump per orbit Δe should be as large as possible. For e not too low so as to have $S_e \approx S$, there results

$$|\Delta e| \propto \frac{m_t}{M_{SC}} \frac{\sigma_c r_p}{\rho_t} S\left(\frac{r_p}{R_J}, \frac{L}{(\sigma_c h)^{2/3}}\right). \tag{21}$$

One can easily verify that $|\Delta e|$ is greater the greater are L and the ratio m_t / M_{SC}, and the smaller are h and ρ_t. Also, $|\Delta e|$ increases with decreasing r_p and increasing σ_c

Figure 4 shows S_e steepening with decreasing e after a long stretch at nearly constant value. Getting the apojove fully down to a perijove radius 1.5 R_J could require about 20 perijove passes following capture. The SC would finally be in a low circular orbit around Jupiter. Then, switching on the current over the entire 1.5 R_J orbit would make the SC to spiral inwards to reach some altitude optimal for a full exploration of the planet. Note that the SC will be free of damaging radiation effects once it reaches down to an orbit lying within 1.3 R_J, roughly. Here stands the inner edge of the radiation belt, where belt electrons are lost through a variety of mechanisms that include scattering to the atmosphere of Jupiter, and energy loss through synchrotron emission.

5 - RADIATION DOSE

As regards radiation, there exist two basic modifications of the **D/G** model, which had originally covered the magnetic shell range $1.09 < L < 16$. Late analysis of data from the Galileo *Energetic Particle Detector* led to modifications over the range $8 < L < 16$, in a so called **GIRE (***Galileo Interim Radiation Electron*) model. **GIRE** does reduce the dose rate, as compared with the **D/G** model, at such important locations as the Europa and Ganymede orbits but leaves the $L < 8$ range (dominant as regards radiation) unmodified, and thus has moderate relative effect on the dose per orbit for orbits that reach very close to Jupiter. A second modification of the **D/G** radiation model covers the $L < 4$ range, well in the inner magnetosphere. It arised in recent analyses fitting synchrotron emission data from Earth-based measurements, and affect relativistic (multi-Mev) electron energies. It hardly affects the electron flux except in the narrow range $2 < L < 2.3$, and will be ignored here.

A simple benchmark for estimating radiation effects over the orbit evolution of the tethered spacecraft would be a calculation of dose over the parabolic orbit of capture. Calculations were carried out starting at 15 R_J inwards and ending at 15 R_J outwards, using the GIRE radiation model. Figure 5 shows dose/depth curves for both 1.2 R_J and 1.5 R_J capture perijoves, at 200^o and 290^o West Longitudes in standard SIII coordinates (roughly corresponding to minimum and maximum of dose).

Dose involves both fluence and the stopping power of some shielding material, typically aluminum; for any given shield-thickness, incident particles below some energy will not come out at the opposite side of the shield. As a result, radiation dose, characterizing damage to some reference material (silicon) placed behind the shield, will decrease with increasing shield thickness. A geometrical standard shielding configuration was used in the calculation of radiation dose, the generic code involving an aluminum spherical shell for all 4π stereoradians.

Figure 5 shows that dose is weakly dependent on longitude, reflecting the low values of both tilt and offset of the dipole describing the magnetic field in the inner magnetosphere, which we had just ignored in our analysis of capture and orbit evolution. Independently, at distances so close to Jupiter, dose decreases, though weakly, as the perijove is located closer and closer to the planet. Full dose over the radiation capture is about 40 krad *Si* for 10 mm shielding thickness. It is generally accepted that electronic equipment to use in future Jovian missions will need be hardened well over 1 Mrad *Si*, with shield thickness equivalent to 10 mm *Al*, though using a tantalum shield to reduce mass has been suggested.

If one proceeds along a sequence of orbits of decreasing apojove, comparable values of dose per orbit result. Figure 6 shows the dose increment per orbit, for two perijove values, versus eccentricity (or equivalently, apojove); the dose increment first increases, then decreases, as e is reduced. Figure 7 presents the accumulated dose for two sequences of orbits corresponding to moderate decrements of eccentricity per orbit. Circular orbits around Jupiter, below the radiation belt, can be reached with an accumulated dose around 1-2 Mrad. The SC could make over 20 flybys of Io, before the accumulated dose exceeds a 3 Mrad value, the total time since the perijove capture being abover one month. It would take about 10 flybys of Ganymede to reach a similar dose, the corresponding duration being about nine.

6 - LOW ORBIT AROUND IO

Once the apojove of a tethered spacecraft has reached down to the Io torus, an orbit evolution alternative to a series of flybys might get the SC into a low circular orbit around Io. The operation would involve switching off the current at each perijove pass and switching it on within the torus, around apojove, to produce thrust. Use of the high plasma density inside the torus may then lead to an inverted process of orbit evolution, with apojove fixed and perijove progressively increased, with the eccentricity decreasing, however.

As regards the torus model, early 2D models must be adjusted by a later correction arising from a factor of 2 error in published ion temperatures; this results in a torus more extended latitudinally. The radial density profile in the torus, which is actually slightly tilted with respect to the Jupiter equator, exhibits peaks and troughs. In general, possible temperature differences among species and temperature anisotropies, as well as the fact that electron temperature catches up with ion temperature when moving from the center to the inner region of the torus keep a degree of uncertainty in torus thickness. Late Voyager data indicate greater latitudinal broadening in the "ribbon" torus region from 5.7 R_J to 5.9 R_J. Also, later Galileo data suggest plasma density in the torus is higher by a factor of 2 than indicated by Voyager.

We note that the radial density profile used in the plasmasphere refers to distances in a plane tilted, with respect to the equator, 2/3 of the small magnetic-dipole tilt with respect to the spin of Jupiter, which is about 9.6°; the density scale height perpendicular to that plane, however, is large enough in the plasmasphere to allow using that profile for our equatorial- orbit calculations. On the other hand, the (ion) temperature in the inner torus gets so low that the scale height is small enough for the torus tilt to affect the plasma density found by a SC in an equatorial orbit (the small angle, 6.4°, of the tilted plane still allows use of r as radial distance in the equator itself). The density is thus longitude dependent.

The speed of the corotating torus is about $(5.9 / 2.24)^{3/2} \approx 4.27$ times greater than the speed of Io, which moves itself faster than the SC when in its apojove neighbourhood, inside the torus, in any of the successive elliptical orbits. The longitude at the SC position will thus vary fairly rapidly as the torus sweeps past it. We simplified calculations by averaging over a full torus revolution to get a 'mean' electron density to use in determining tether currents. Errors arising from the fact that the torus-to-SC speed ratio is only moderately large should be broadly washed out by the fact that the number of orbits required to raise the perijove to the torus is itself found large.

Cumbersome but straighforward calculations yield the work for arbitrary eccentricity, $W_{e/t}$, as an integral over a thrust arc,

$$\frac{W_{e/t}}{m_t v_\infty^2 / 2} = \tilde{B}_s^2 \; I_o\left(\frac{r_a}{R_J}, \frac{\hat{\lambda}}{\tilde{B}_s^{4/3}}, e\right) \tag{22}$$

As with drag work in Sec.3, thrust acts over the entire elliptical orbit, from perijove to apojove and back, when the eccentricity is already low enough. Equation (1) can be rearranged to read as

$$\varepsilon = \frac{-\mu_J}{2r_a}(1+e) \qquad \Rightarrow \qquad \Delta e = -\frac{2r_a}{\mu_J}\Delta\varepsilon . \tag{23a, b}$$

Use of $\Delta\varepsilon = W_{e/t}/M_{SC}$ and Eq. (22) finally gives

$$|\Delta e| \propto \frac{m_t}{M_{SC}} \frac{\sigma_c r_a}{\rho_t} I_o . \tag{24}$$

Figure 8 shows I_o versus eccentricity, for apojove at 5.9 R_J, at the Io orbit, and several values of parameter $\hat{\lambda}$.

Comparing Eqs. (21) and Eq. (24), and Figs. 4 and 8, shows dramatically that raising the perijove from near Jupiter to the Io torus will require a very large number of apojove passes. Basically the low I_o values are a result of a dipole magnetic field decreasing as the cubed inverse power of distance; for the weak ohmic effects case of interest, the Lorentz force will roughly vary locally as BN_e, "mean" plasma densities in the torus being comparable to densities near Jupiter.

Note also that the orbit arc where thrust applies is typically larger than the drag arc in the ratio r_a / r_p; this is reflected in the factor r_a in (24), as compared with r_p in (21), and partially compensates the disparity in S_e and I_0 values. Independently, the full time required for raising the perijove to the torus is actually moderate because each orbit takes less than, or about, one day. The radiation dose accumulated during the entire orbit sequence appears unacceptable, however. Figure

9 presents the dose per orbit versus eccentricity (or equivalently, perijove) for apojove at Io. For r_a = 5.9 R_J and M_{SC} = 3 m_t, Eq.(24) yields

$$|\Delta e| \approx 0.075\, I_0. \qquad (25)$$

Taking I_o (av) = 0.07 as a characteristic value in the $0 < e < 0.59$ range for $\hat{\lambda} = 2^{1/3}$ in Fig. 8, the number of torus passes required to raise the perijove from its initial value 1.5 R_J to the Io orbit would be

$$\textit{Number of apojove passes} \approx 0.59 / 0.075 \times 0.07 \approx 110.$$

The entire sequence might require just about 4 months, ending about 8 months after capture. However, taking 75 krad as a mean dose per orbit from Fig. 26, and adding the 500 krad accumulated in first getting the apojove to the Io orbit, as discussed in Secs.7.2 / 7.3, would yield a total dose over 8.5 Mrad *Si* behind 10 mm *Al* shielding for carrying the SC into low orbit around Io. As with Eq. (21), $|\Delta e|$ is greater the greater are L, σ_c and the ratio m_t / M_{SC}, and the smaller are h and ρ_t.

7 - CONCLUSIONS

Following capture, repeated application of Lorentz drag at perijove passes can efficiently lower the orbit apojove. This can give raise to three different mission profiles:

Mission 1. A tethered SC could rapidly and frequently visit Galilean moons. Elliptical orbits with (capture) perijoves at about r_p = 1.5 R_J and apojoves down at the Io, Europa and Ganymede orbits, are in resonances 1:2, 4:9, and 2:5 with the respective moons. About 20 *slow* flybys of Io could take place before the accumulated radiation dose exceeds 3 Mrad *Si* at 10 mm *Al* shield thickness, for a total mission duration of about five months after capture. The respective number of flybys for Ganymede would be 10, with total duration less than nine months.

Mission 2. - A tethered SC could acquire a safe, low circular orbit around Jupiter (below the radiation belts) and manoeuvre to get an optimal altitude, with no major radiation effects in just over 4 ½ months after capture.

Mission 3. - By thrusting at the apojove once reached the torus, to raise the perijove from the plasmasphere, a tethered SC could acquire a low circular orbit around moon Io in about 4 months, or 8 months after capture. The accumulated radiation dose, about 8.5 Mrad *Si*, poses a critical issue. Using electrical energy generated over high-current segments of orbits, and saved/stored in regenerative fuel cells / batteries, might, however, power electric propulsion at critical thrusting needs for Mission 3.

As seen elsewhere, design parameters, tape length L and thickness h, and perijove radius r_p, face opposite criteria. A high mass-ratio M_{SC} / m_t requires a low perijove and a high $L^{3/2}/h$ ratio. But tensile strength and tether bowing considerations, arising from the tether spin required by the low gravity gradients and high lateral Lorentz forces at Jupiter, may place a bound on the ratio $L^{5/2}/h$. Also, heating and radiated power keep tether temperature in thermal equilibrium both local and quasisteady. (In the weak ohmic effects limit, heating arises from the impact of collected electrons, and maximum temperatures occur at tether ends, even though they only receive heating when acting anodically, i.e. half the time.) Maximum tether temperature scales as $L^{3/8}$. In addition, both tether temperature and bowing are greater the closer to Jupiter is the perijove.

A preliminary design that sets the perijove at 1.5 R_J, chooses a mass ratio $M_{SC} / m_t \approx 3$, and uses a reinforced *Al* tape, about 80 km long and 0.05 thick, coated for thermal emittance $\varepsilon_t \approx$ 0.8, with a 20 minutes spin, appears to satisfy all constraints. No characteristic dimensionless number involves the tape width. The spacecraft mass will just scale up with width in a range allowing from about 0.5 to 5 tons. For a 3 cm wide tape, m_t and M_{SC} would be 324 kg and 972 kg respectively. We note that tether capture by Saturn, where B_s is 20 times smaller than at Jupiter, appears impossible.

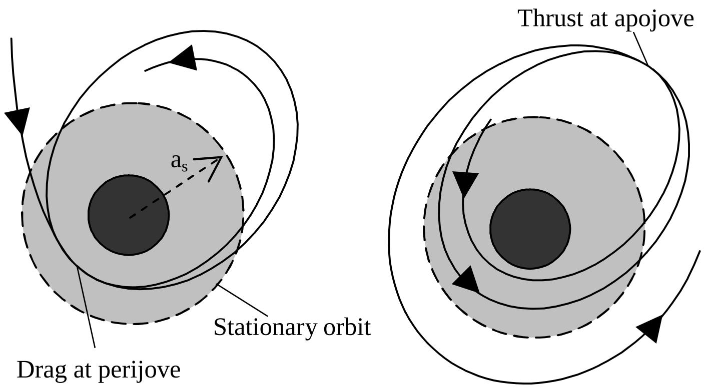

Fig. 1. Jovian tour phases: Capture and lowering apojove. Raising perijove.

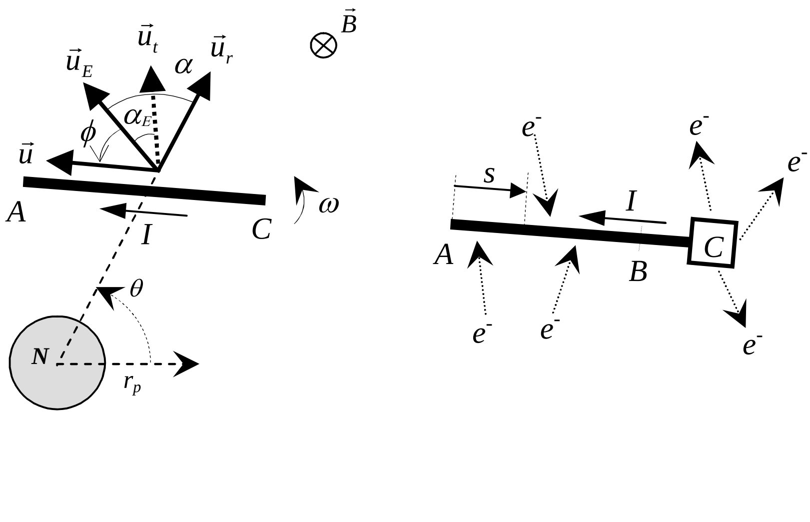

Fig. 2 (a) Relative positions of unit vectors for motional electric field and spinning tether, as in Fig.3; A and C are the anodic and cathodic ends, respectively.

(b) Sketch of bare-tether operation. Electrons are collected over an anodic segment from end A to some point B. Bias is negative to the right of B; ion collection over the cathodic segment BC comes out to be negligible. Electrons are ejected at the hollow cathode at C. The hollow cathode at end A is off.

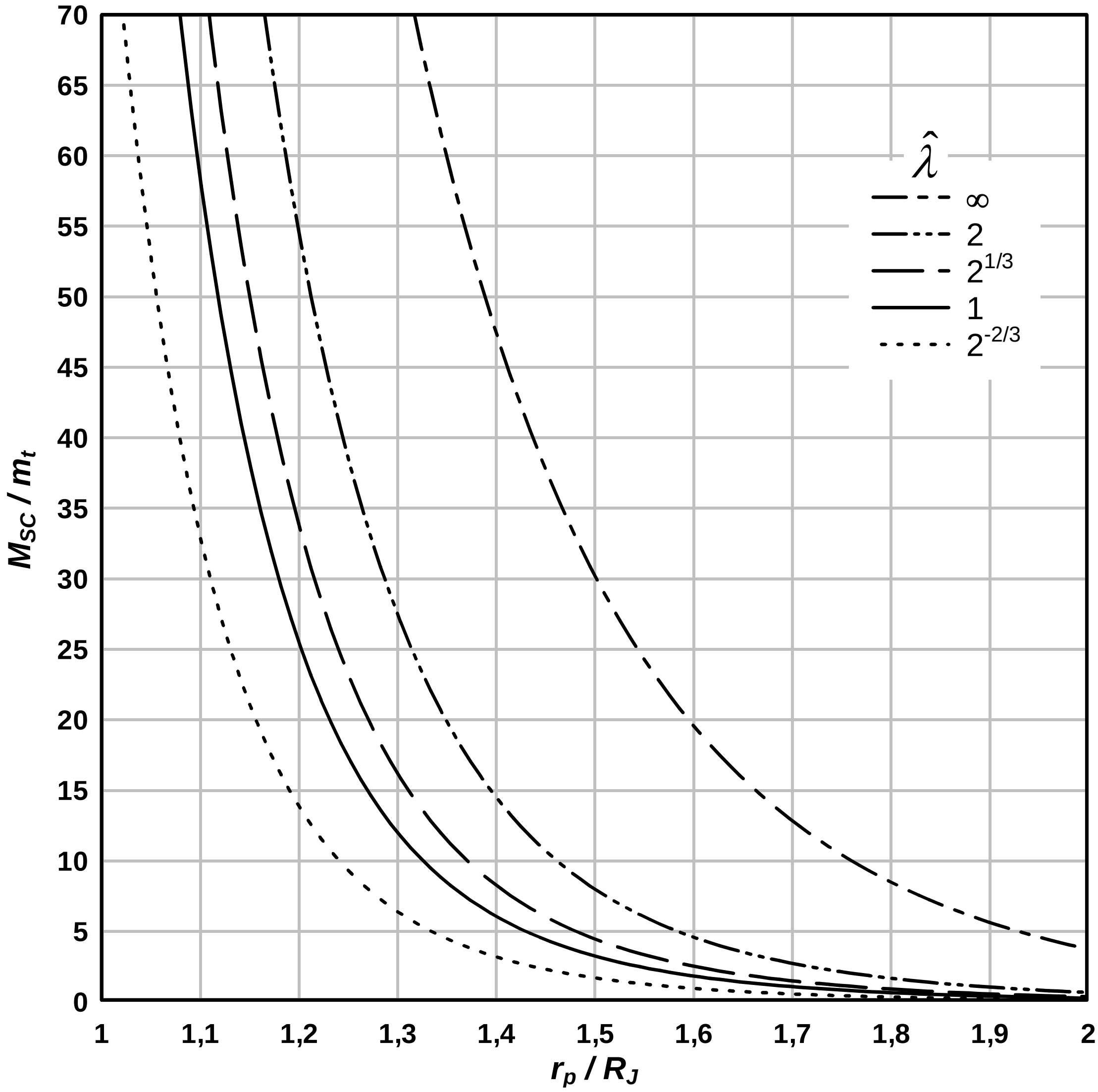

Fig. 3 Mass ratio versus perijove position for $1 - e_1 = 0^+$, and several values of parameter $\hat{\lambda}$ in Eqs. (18a, b)

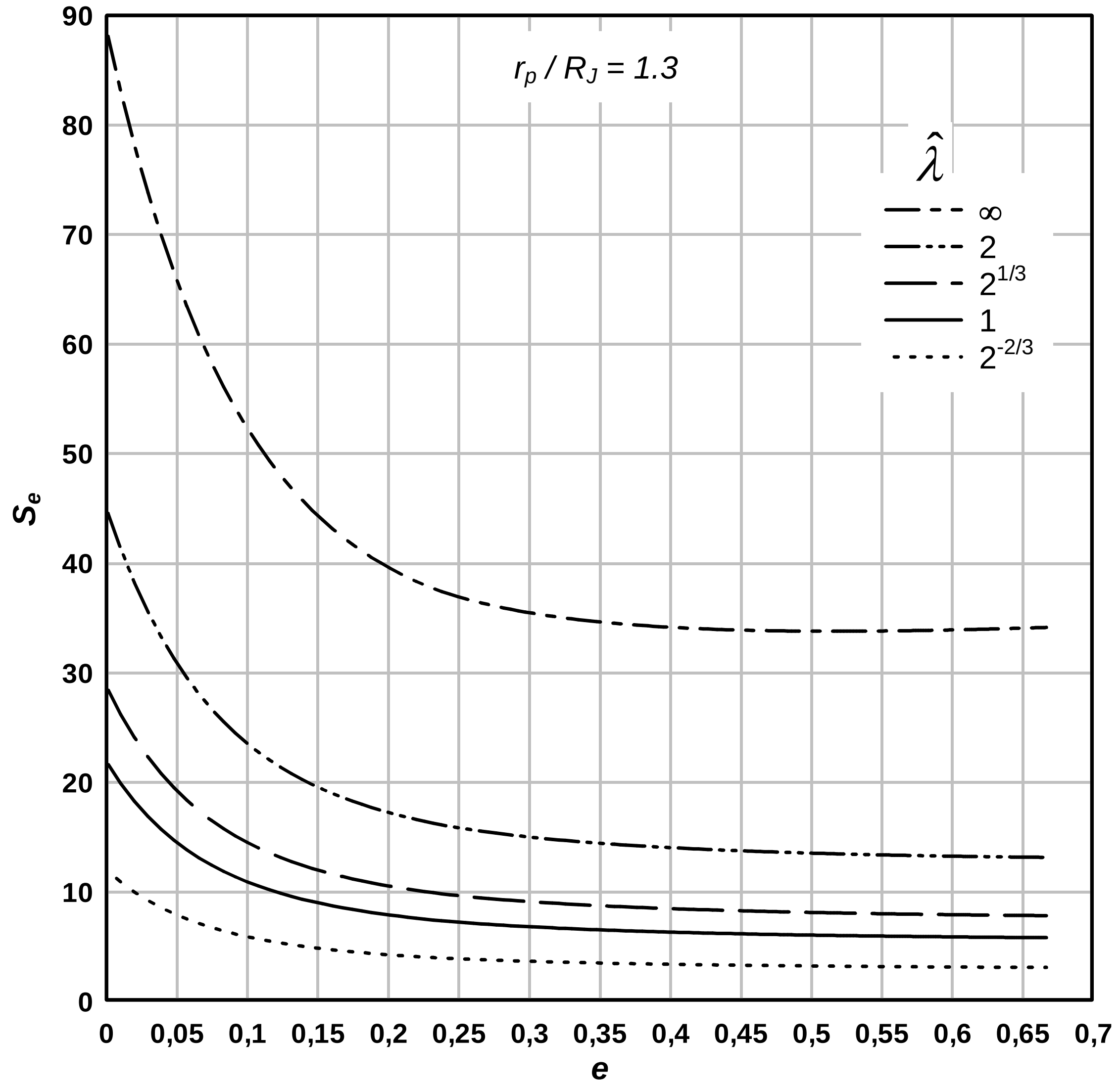

Fig. 4 Factor S_e in Eq. (20) for drag work per orbit versus eccentricity for $r_p = 1.3\ R_J$

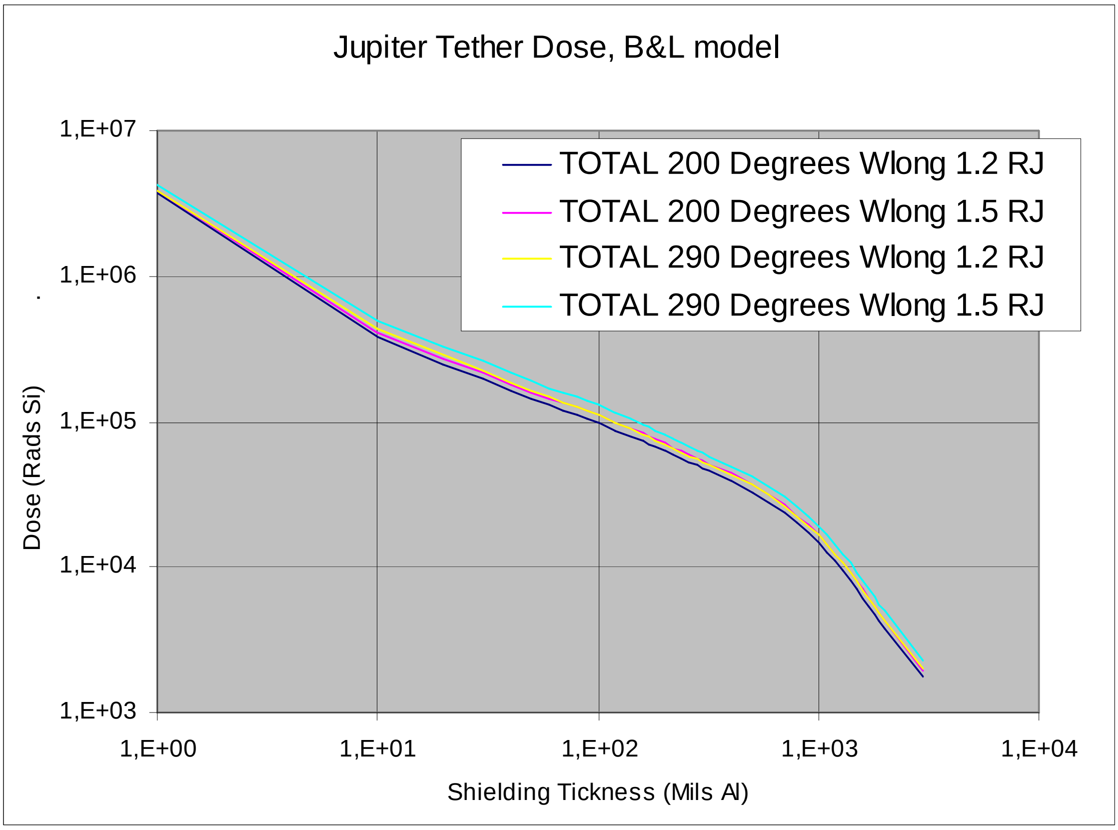

Fig. 5 Total dose-depth curves for an equatorial and parabolic orbit of capture for perijoves at two radii and two West Longitudes (R.W. Evans).

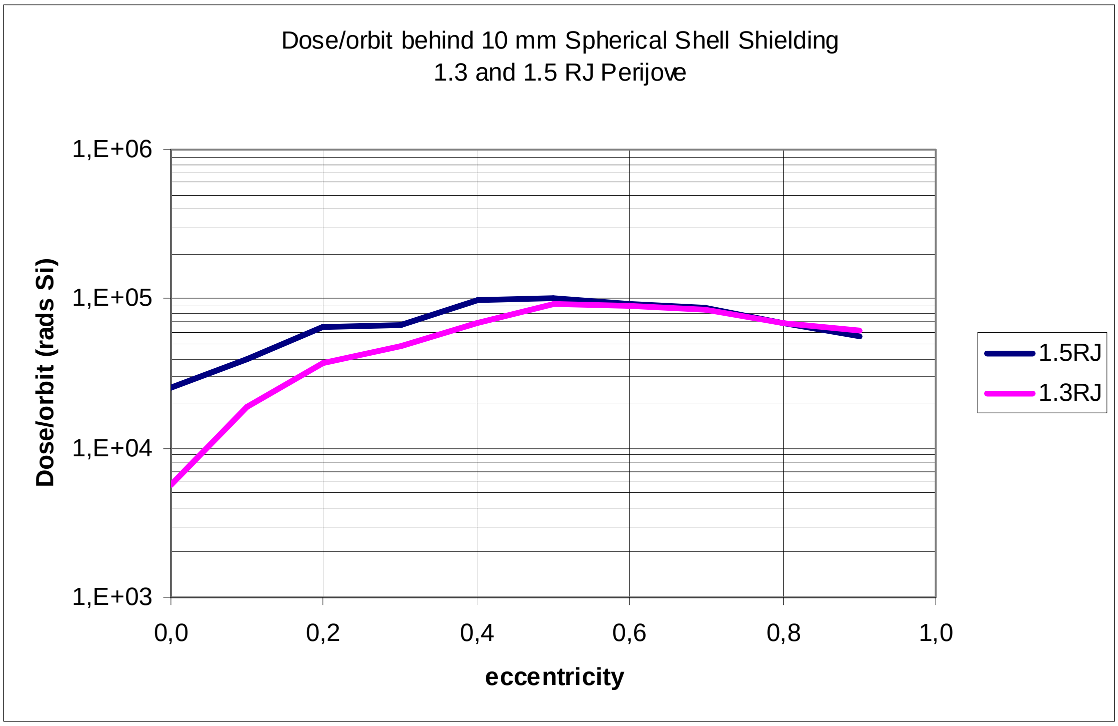

Fig. 6 Radiation dose per orbit for two perijove values and 10 mm *Al* shield thickness

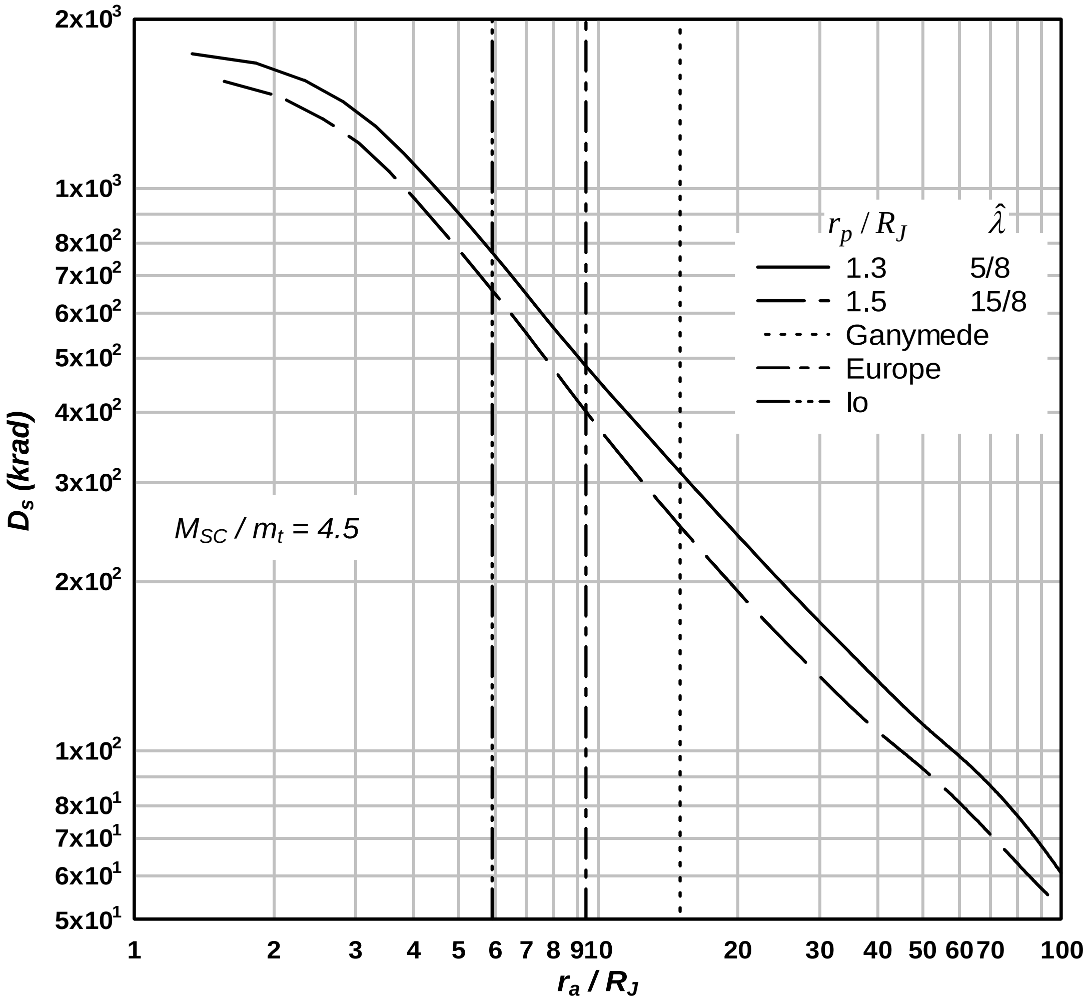

Fig. 7 Radiation dose accumulated over the sequence of orbits, from capture down to any particular apojove radius, for two combinations of perijove position and parameter $\hat{\lambda}$ resulting in moderately small eccentricity decrements per orbit (10 mm Al shield thickness). Distances from moons to Jupiter are marked.

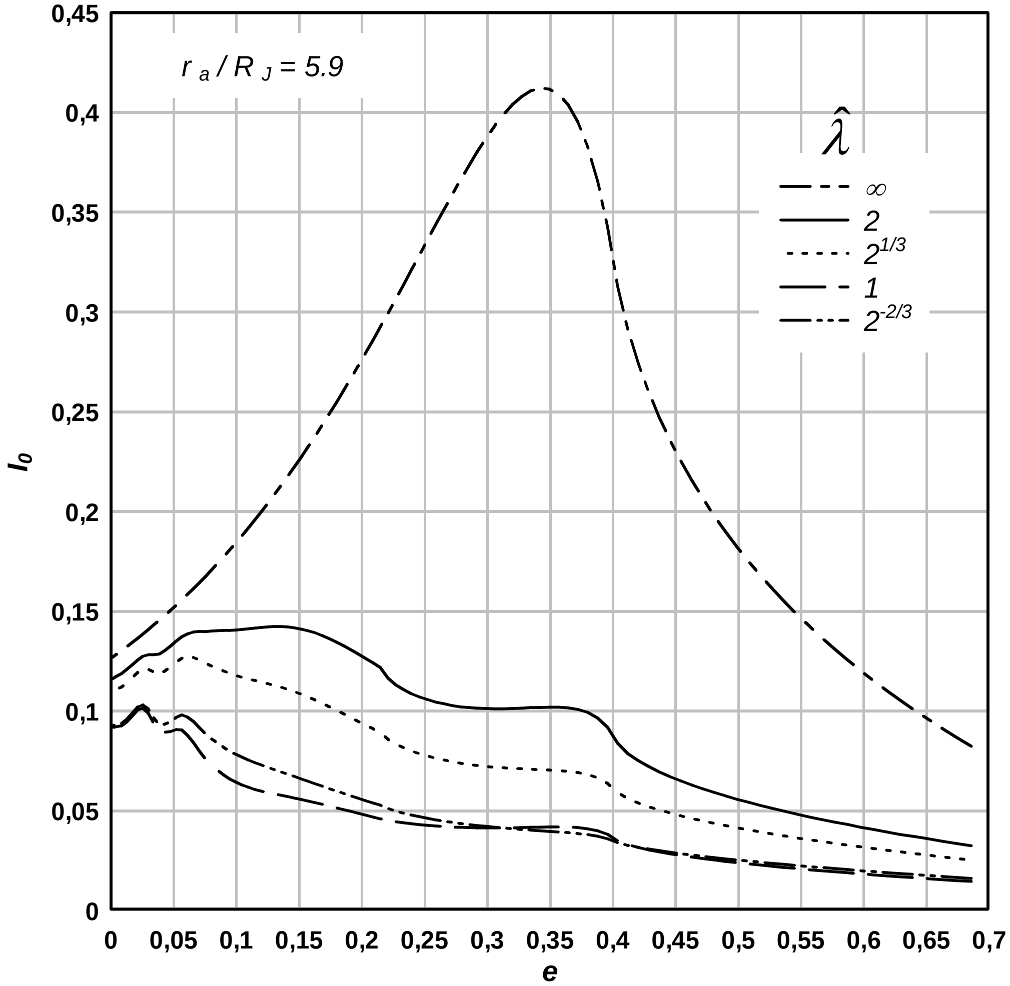

Figure 8. Function I_0 in Equation (22) versus eccentricity, for apojove at 5.9 R_J, several values of parameter $\hat{\lambda}$.

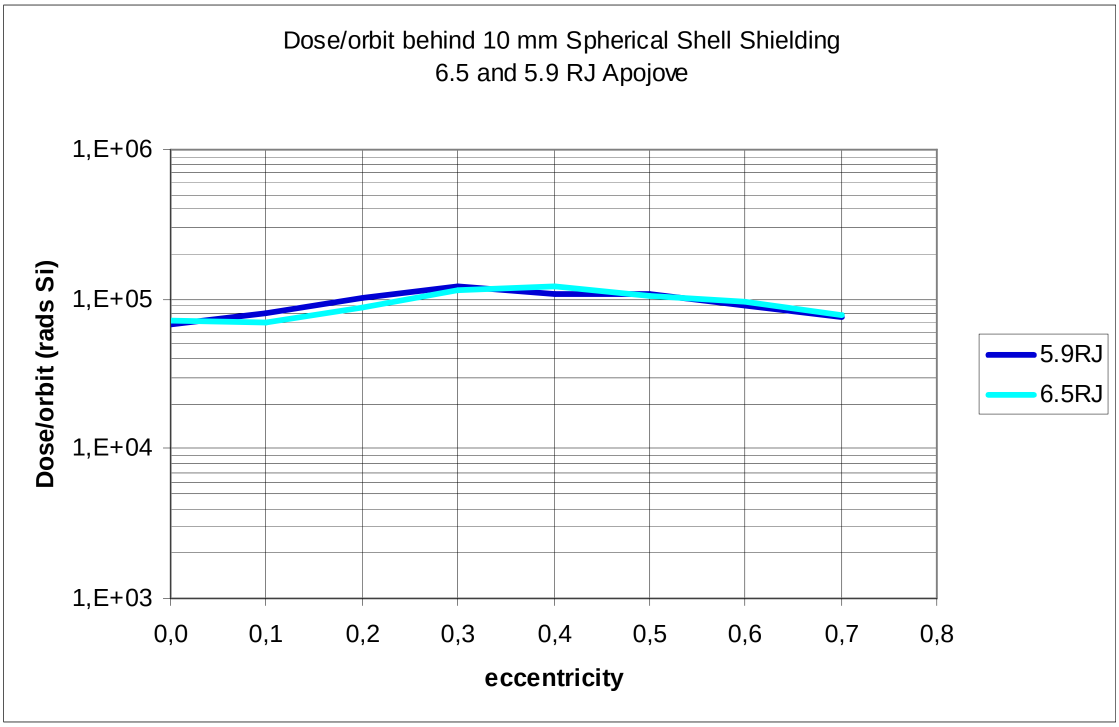

Fig 9 Radiation dose per orbit versus eccentricity for apojove at the *Io* orbit, and 10 mm Al shield thickness (*R. W. Evans*).

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