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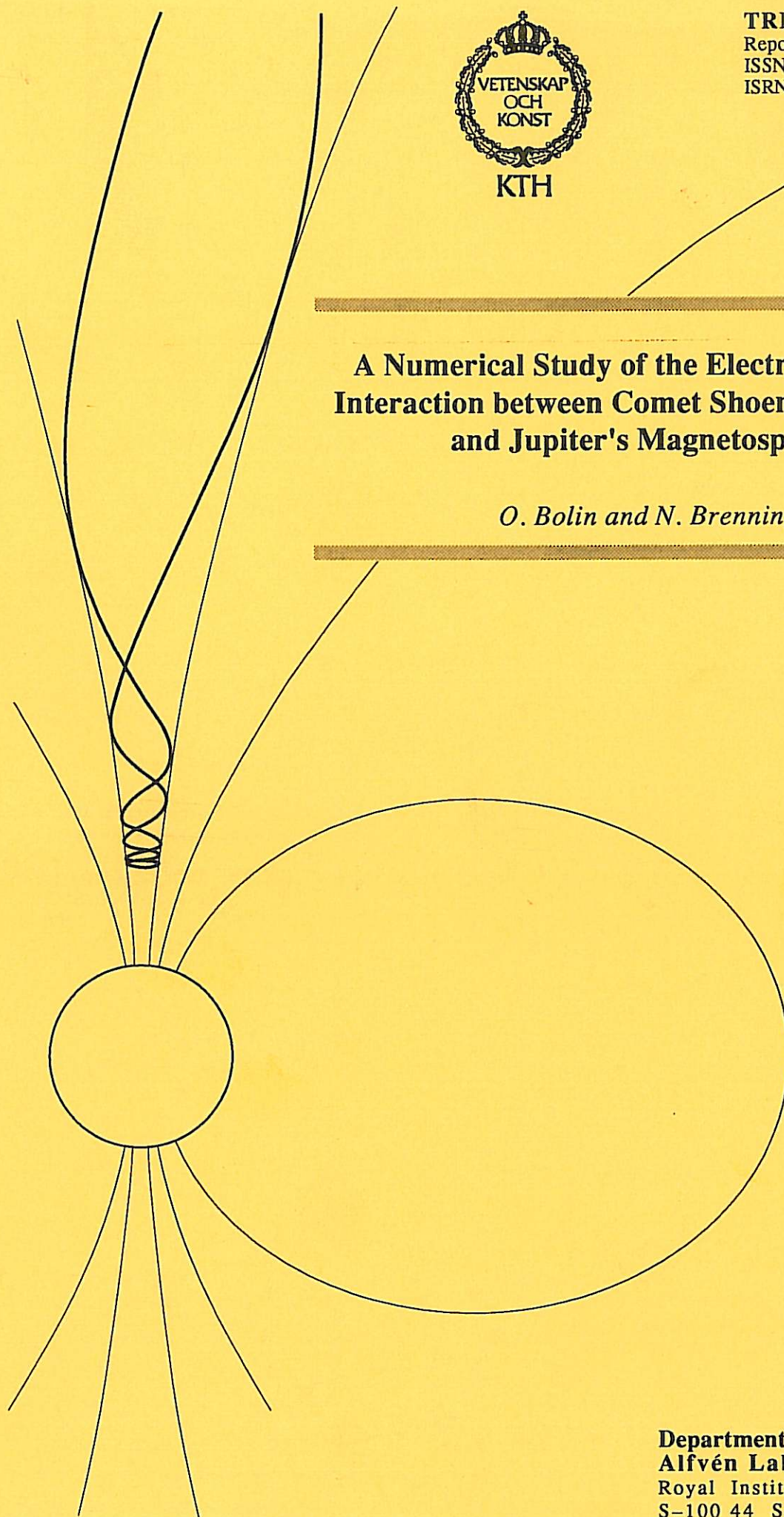
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A Numerical Study of the Electrodynamical Interaction between Comet Shoemaker-Levy 9 and Jupiter's Magnetosphere

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A NUMERICAL STUDY OF THE ELECTRODYNAMICAL INTERACTION BETWEEN COMET SHOEMAKER-LEVY 9 AND JUPITER'S MAGNETOSPHERE

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Abstract

The electrodynamical interaction between Jupiter and comet Shoemaker-Levy 9, which is expected to impact on Jupiter around July 20, 1994, is investigated using a numerical model. The comet consists of a sequence of 21 or so nuclei, each surrounded by a neutral cloud of outgased material. A model is constructed of one single such cloud which is subject to electron impact ionization during the passage through Jupiter's magnetosphere. The cloud is assumed to couple electrically to the surroundings either by means of Alfvén wings analogous to the Jupiter-Io connection, or through a dc circuit that closes in Jupiter's ionosphere. The magnetic-field-aligned currents resulting from the Jupiter-Io interaction are strongly connected to the Jovian Decametric Radiation. The Shoemaker-Levy comet can theoretically supply ions to Jupiter's magnetosphere at a rate not so far below Io's, and will have a higher velocity relative to Jupiter, and could therefore conceivably drive similar processes. However, we find that, due to the high latitude trajectory of the comet, the resulting currents become very weak. The field-aligned currents obtained in this study are a factor 500 below those driven by Io, while the dissipated power is almost a factor of 10^6 below. It is therefore proposed that very little or no detectable electromagnetic radiation will arise during the comet's passage through Jupiter's magnetosphere.

1. Introduction

Before colliding with Jupiter around July 20, 1994, comet Shoemaker-Levy 9 will pass through and interact with the Jovian magnetosphere. The comet consists of a train of 21 or so nuclei surrounded by neutral gas clouds (Powell, 1993). Because of electron impact ionization and photo-ionization the neutral clouds will become partly ionized when they pass through the plasma in the magnetosphere. The ionization rate will vary with the ambient plasma density and electron temperature. Both the comet's motion towards Jupiter and the co-rotation of the Jovian magnetosphere inside 20 R_J contribute to give the plasma in the clouds a velocity across $\mathbf{B}$, and thus an induced electric field is produced in the comet's rest frame. We here discuss the possibility that the electrodynamical interaction between Jupiter and the ionized comet clouds might drive processes which can be observed prior to the impact of Shoemaker-Levy 9 on Jupiter itself. Fortunately there is already a suitable object in the Jovian magnetosphere on which to base a model for such interaction: the Jupiter-Io system has been described as an archetype for the coupling between a large conductor and a magnetized plasma in relative motion. In the Jupiter-Io system, currents of several MA flow long distances along the magnetic field before they close, partly across $\mathbf{B}$ in the ambient plasma, and partly down in Jupiter's ionosphere. Associated with these currents is the Jovian Decametric Radiation, one of the strongest radio sources in the solar system, and for which the excitation mechanism is still not completely understood. Before the Voyager spacecraft encounters, this system was believed to be most accurately described by a dc circuit model, where the magnetic-field-aligned currents closed in Jupiter's ionosphere, the relevant parameter being the height-integrated Pedersen conductivity (Goldreich and Lynden-Bell, 1969). The validity of this model was based on the assumption that the time taken by an Alfvén wave to complete the round trip between Io and the ionosphere (the "bounce time") is considerably less than the time it takes for Io to cross its own magnetic flux tube. However, the high plasma densities measured by Voyager in Io's plasma torus significantly increased the estimates of the bounce time, making the Alfvén wing model by Drell *et. al.* (1965) seem the more plausible one (Belcher, 1987). In this model the field-aligned currents are carried by Alfvén waves, closing partly across $\mathbf{B}$ in the ambient plasma, and partly in Jupiter's magnetosphere. The relevant parameter is now the Alfvén conductivity in the magnetospheric plasma.

The orbit of comet Shoemaker-Levy 9 is such that it will approach Jupiter at very high latitudes, particularly in the inner part of the magnetosphere. There the plasma density, according to the existing models (Divine and Garrett, 1983) is very low, resulting in a high Alfvén velocity, and it is not very clear whether the dc circuit model or the Alfvén wing model is the appropriate one for the electrodynamical interaction between the comet and Jupiter. We have therefore made calculations using both these alternatives. We have constructed a numerical model of the neutral cloud around one single

cometary nucleus, and calculated the combined electron impact and photo-ionization rate as a function of radial distance from the nucleus, and as a function of the nucleus' position in the magnetosphere. These spatially distributed ionization rates are then combined with the ambient plasma parameters to calculate the field-aligned current density, the total current, the electric power output and the mapped-down current density (along the magnetic field down to Jupiter's ionosphere). The main result is that, due to the high latitude orbit of the comet in the Jovicentric frame, the currents and current densities from the comet become very low, particularly in comparison with the currents in the Jupiter-Io system. At high latitudes the plasma density in the inner Jovian magnetosphere, is, according to the available *in situ* measurements and magnetospheric models, extremely low, in the order of 10^4 m^{-3} or lower. This low magnetospheric plasma density results in a very low electron impact ionization rate, and consequently small currents. Since the field-aligned currents between Io and Jupiter are generally considered as the main cause of the Jovian Decametric Radiation, we therefore predict that any electromagnetic radiation caused by the interaction between comet Shoemaker-Levy 9 and the Jovian magnetosphere will be rather insignificant and very difficult to detect.

2. Model

In our model for a single cometary nucleus we use OH as the dominant molecule (Cochran, private communication, 1993). However, for lack of good estimates of the physical properties of OH under the conditions studied here, we use H_2O for two of the model parameters, namely the radial out-gasing velocity and the photo-ionization time constant. The neutral gas density in the cloud around the nucleus can be calculated as follows: During a time interval dt p•dt atoms, where p is the production rate, will be produced by the comet nucleus. If we assume that all the atoms leave the nucleus with the same radial velocity v_r, these atoms will at a time t occupy a radial shell having a volume

$$V = \frac{4\pi}{3}(r_c + dr_c)^3 - \frac{4\pi}{3}r_c^3 \tag{1}$$

where $r_c = v_r \cdot t$ and $dr_c = v_r \cdot dt$. If dt<<t then

$$V \approx 4\pi r_c^2 dr = A v_r dt \tag{2}$$

where A is the area of the shell. The neutral gas density at r_c then becomes

$$n_n = \frac{p \cdot dt}{V} = \frac{p}{A v_r} \tag{3}$$

We use a production rate p=3.5•10^{27} s^{-1} for OH, which is the upper limit found by Cochran (private communication, 1993), and a radial out-gasing velocity (for H_2O) v_r=1 km•s^{-1} (Rickman, private

communication, 1993). These values then gives the neutral density in the cloud as $n_n = 2.78 \cdot 10^{23}/r_c^2$ [m^{-3}], where r_c is given in m. As the comet moves through the plasma in the Jovian magnetosphere, the neutral gas will become ionized both due to collisions with hot electrons, and due to photo-ionization. The ionization time for an individual neutral is everywhere in the magnetosphere so long that, for our cloud sizes of interest, the decrease of n_n due to ionization can be neglected. We will first discuss the situation at such distances from the cometary nucleus that the new ions constitute a weak mass-load on the magnetic flux tube at which they are injected. The newly created cometary ions and electrons will then be picked up by Jupiter's magnetic field and give rise to a polarization current density $\mathbf{j}_\perp$ that is given by the total momentum change of the ions:

$$\mathbf{j}_\perp \times \mathbf{B} = m_i \frac{dn_i}{dt} \mathbf{v}_{rel} = m_i n_n \left[\tau_{photo}^{-1} + n_e <\sigma_i v_e> \right] \mathbf{v}_{rel} \tag{4}$$

where m_i is the mass of the cometary ions, dn_i/dt is the total ionization rate, n_n is the neutral density in the cometary cloud, τ_{photo} is the photo-ionization time constant, n_e is the electron density, $<\sigma_i v_e>$ is the rate coefficient for electron impact ionization, and $\mathbf{v}_{rel}$ is the relative velocity (perpendicular to the magnetic field) between the co-rotating magnetospheric plasma and the comet. Using an estimate for H_2O, τ_{photo} is set to 25 days (Rickman, private communication, 1993). For electron impact ionization we use a cross section with a threshold energy of $W_i = 10.3$ eV and a maximum of $3 \cdot 10^{-20}$ m^2 at $W_e = 6W_i$. For a Maxwellian distribution of electrons, this gives the impact ionization rate coefficient (Raadu, quoted in Brenning, 1982):

$$<\sigma_i v_e> = \frac{3.55 \cdot 10^{-14} T_e^{1/2} \exp(\frac{10.3}{T_e})}{1.0 + 1.8 \cdot 10^{-2} T_e} \, [m^3 s^{-1}] \tag{5}$$

where T_e is the electron temperature in eV. For n_e and T_e we have used the model of the cold plasma population in Jupiter's magnetosphere given by Divine and Garrett (1983). This model is based on spacecraft measurements close to the Jovian equator and extrapolated to the higher latitudes where comet Shoemaker-Levy 9 will pass; this introduces some uncertainties which we will return to in the discussion. (It should also be noted that this model of the magnetospheric plasma uses the radius r rather than the L number as the relevant distance parameter. This is equivalent to assuming that the magnetic field lines are circles centred on Jupiter, clearly a very crude assumption. The model can however still be used for our purposes, since it for $r<4$ R_J gives a plasma density that is independent of latitude, while for r larger than 4 R_J the plasma density according to the model decreases very rapidly with increasing latitude, resulting in small absolute errors.)

The hot electron density will be depleted in the centre of the cometary cloud where the electron mean free path for inelastic collisions is smaller than the cloud radius. This depletion is calculated as follows: The column density of neutral atoms in the comet cloud is

$$n_c = \int_{r_c}^{\infty} n_n \, dr_c'$$

(6)

We assume that the total cross section for inelastic collisions σ_{inel} is three times the cross section for ionization, $\sigma_i = 3 \cdot 10^{-20}$ m^{-2}. The number of collisions an electron has to go through in order for it to decrease its energy below the ionization energy is given by

$$f(T_e) = \frac{<W_e> - W_i}{W_i}$$

(7)

where $<W_e> = 3kT_e/2$ is the average thermal energy of the ambient electrons, and W_i is the ionization energy. The electron density $n_e(r_c)$ as a function of distance to the centre of the comet is then given by

$$n_e(r_c) = n_e(\infty) \exp(-\frac{n_c \sigma_{inel}}{f(T_e)})$$

(8)

n_e is the number of electrons per unit volume that have an energy $\geq W_i$. Multiplying $n_n <\sigma_i v_e>$ by this expression for n_e gives dn_i/dt as a function of r_c.

The perpendicular current obtained from Eq. (4) draws currents $j_{//}$ parallel to the magnetic field from the ambient magnetosphere:

$$j_{//} = \int_0^{\infty} \text{div} \, \mathbf{j}_{\perp} \, dz$$

(9)

Although the integration is along the magnetic field lines, the relevant scale length is perpendicular to the magnetic field (see Figure 1): the main contribution to the integral along each individual field line comes from $l < r_{\perp}$, where $r_{\perp}$ is the distance across $\mathbf{B}$ from the field line to the cometary nucleus.

According to the Alfvén wing model of Drell et. al. (1965), these parallel currents are carried by Alfvén waves launched along the magnetic field lines. The current system is closed across $\mathbf{B}$ in the fronts of the waves until they reach Jupiter's ionosphere. There, they can either close as Pedersen currents, or the wave can be partially reflected depending on the impedance matching. For calculations on this current system we have assumed the magnetic field to be that of a dipole, which for our

purpose is a good enough approximation.

We consider only spatial scales larger than the ambient ion gyro radius and time scales slower than the ambient ion gyro time. Under these conditions the concept of Alfvén conductance (Mallinckrodt and Carlson, 1978) applies and the electric field $E_\perp$ perpendicular to B along the flux tube can be calculated from the parallel current density as

$$\text{div } E_\perp = \frac{1}{\Sigma_A} j_\parallel \tag{10}$$

where $\Sigma_A = 1/\mu_0 V_A$ is the Alfvén conductance, $V_A = B/(\rho_m \mu_0)^{1/2}$ is the Alfvén velocity, and ρ_m is the ambient plasma's mass density. Eq. (10) applies only when $V_A \ll c$, which is not always satisfied in our case. We therefore present solutions only for cometary positions where $V_A < 0.5c$. Figure 1 shows the cloud model.

This description requires that the mass of the ions created within a flux tube during a time interval Δt is smaller than the mass covered by the Alfvén wave during that time, which Haerendel (1982) has called the weak mass-loading case:

$$\frac{dn_i}{dt} \frac{L_\parallel}{2} m_i \Delta t \ll V_A n_{i,amb} m_{i,amb} \Delta t \tag{11}$$

where $L_\parallel$ is the extent of the comet along the magnetic field, $n_{i,amb}$ is the ambient ion density and $m_{i,amb}$ is the mass of the ambient ions. As ambient ions we have used S^+, which is the most common species found in the Io torus (Belcher, 1987). In the weak mass-loading case most of the cometary ions and electrons will be picked up by the magnetic field, resulting in an electric field $E = v \times B - E_\perp$ in the comet's coordinate system. $E_\perp$ is the small polarization electric field caused by the finite Larmor radius of the cometary particles. In Jupiter's coordinate system the electric field across the cloud is then $E_\perp$. Moving to the strong mass-loading case (Eq. (11) with a $\gg$ sign), the cloud imposes its self-polarization electric field $E_p = -v \times B$ on the flux tube. This is the electric field as seen in Jupiter's coordinate system. In the comet's coordinate system the total electric field now becomes close to zero. $E_\perp$ as calculated from Eq. (10) is the electric field as seen in Jupiter's rest frame, although at the position of the comet (since the Alfvén conductance is calculated at the position of the comet). We have chosen to truncate the $E_\perp$ field at the radius where it reaches E_p, setting it constant inside (consequently with Eq. (10) giving $j_\parallel = 0$ within that region).

The electric field calculated from Eq. (10) is not self-consistent. The displacement of the ions relative to the electrons that creates the parallel currents also results in an electric field outside of the cometary

cloud. The total electric field is a superposition of the electric field from Eq. (10) and this external electric field. At some distance from the centre of the comet the total electric field becomes zero, see Figure 2. This gives a maximum radius where Eq. (10) can be used to find a reasonable approximation of the electric field inside the cometary cloud. We have calculated estimates of that radius by using the expression for the electric field from a line dipole (which is valid for $(x^2+y^2)>R$):

$$E= \frac{\rho_s}{2\varepsilon_0} \left[\frac{(x^2-y^2)R^2}{(x^2+y^2)^2} , \frac{2xyR^2}{(x^2+y^2)^2} , 0 \right] \tag{12}$$

where ρ_s is the surface charge density at x=R, y=0. The coordinate system is shown in Figure 1. The z axis is along the magnetic field and the y axis along v_{rel}, the perpendicular component of the vector of relative motion between the comet and the co-rotating magnetosphere. (The direction of the y axis thus changes direction with respect to Jupiter as the comet moves through the magnetosphere. Figure 3 shows the approximate orientation of the coordinate system at radial distances large enough for the co-rotation to dominate.) The surface charge density can be calculated from the parallel current density using div $E_\perp =\rho/\varepsilon_0$, where ρ is the volume charge density. Multiplying ρ by a typical scale length for the charge density variations perpendicular to **B**, in this case the Larmor radius r_L for the cometary ions, gives ρ_s. The external electric field at a point x=R_c, y=0 can then be approximated by integrating Eq. (12) from x=$r_{c,min}$ to x=R_c:

$$E_{ext}(x=R_c,y=0) \approx \left[\int_{x=r_{c,min}}^{x=R_c} \frac{\rho r_L}{2\varepsilon_0} \left(\frac{x}{R_c} \right)^2 \frac{dx}{r_L} , 0 , 0 \right] \tag{13}$$

$r_{c,min}$ is the radius of the cometary nucleus. By setting $|E_{ext}|=|E_\perp|$ an estimate of the maximum radius inside which Eq. (10) is valid can be found.

As mentioned above, the Alfvén wing model has shown remarkable agreement with the Voyager 1 measurements close to Io's flux tube (Belcher, 1987). This agreement is in fact our main justification for using Eq. (10), which strictly applies only to a homogeneous ambient plasma, in spite of the fact that the Alfvén waves pass through regions of variable plasma density and magnetic field on their way down to Jupiter.

According to the dc circuit model (Goldreich and Lynden-Bell, 1969), the field-aligned currents are closed only in the ionosphere, and Eq. (10) is replaced by

$$\text{div } \mathbf{E}_\perp = \frac{1}{\Sigma_P} j_{//} \tag{14}$$

where Σ_P is the height-integrated Pedersen conductance, and $\mathbf{E}_\perp$ now is the perpendicular electric field in the ionosphere. In a steady-state situation with $E_{//}=0$, $\mathbf{E}_\perp$ can be mapped to the comet proportional to $\sqrt{B}$. We have chosen to truncate $\mathbf{E}_\perp =E_p$ in this model too. The value of Σ_P is set to $0.1 \ \Omega^{-1}$ (Dessler and Hill, 1979).

For the calculations we have solved Eq:s (4), (9), and (10) or (14) numerically in a cubical grid space. The grid size is 1 km, close to the most recent estimates of the radii of the brightest cometary fragments (A'Hearn and McFadden, 1993), and there are 250^3-500^3 grid cells. Current densities, total current, spatial current distribution, and total power have been calculated a functions of the latitude and the distance from Jupiter. We have calculated two different trajectories (a and b) based on the expected comet orbits, see Figure 3 (Lindgren, private communication, 1993, and Chodas, private communication, 1993). These trajectories are intended to include the effects on different cometary fragments caused by the inclination (approximately 7°) between Jupiter's centrifugal equator (the symmetry plane of the magnetospheric plasma model) and the rotational equator. Due to that inclination combined with the co-rotation of the magnetospheric plasma, different cometary fragments will approach Jupiter along different latitudes with respect to Jupiter's centrifugal equator. In order to bench-mark the model against the better known Jupiter-Io system, we have also calculated a hypothetical trajectory (c) through Io's plasma torus.

3. Results and discussion

As mentioned in the introduction, the critical parameter for choosing between the dc circuit model and the Alfvén wing model is the ratio between the time it takes for an Alfvén wave to travel from the comet to the Jovian ionosphere and back (τ_{bounce}), and the time it takes for the comet to cross a magnetic flux tub (τ_{cross}). If $\tau_{bounce}/\tau_{cross} \ll 1$, then a dc circuit can be set up between the comet and Jupiter, where the currents from the comet are closed in Jupiter's ionosphere. If $\tau_{bounce}/\tau_{cross} \geq 1$, the current system will be closed mainly in the fronts of the Alfvén waves that carries the parallel currents. The upper panel of Figure 4 shows the spatial distribution of the field-aligned current in a cross section perpendicular to **B** through the centre of the comet. This distribution is calculated along trajectory b. The distance to Jupiter is 2 R_J. The fraction of the total current flowing within a certain contour is shown. 50% of the total current flows within a radius of approximately 40 km. This can be taken as an "effective radius" of the comet, to calculate τ_{cross}. The lower panel of Figure 4 shows how this effective radius changes along trajectory b. The dotted line shows the radius where

$\tau_{bounce}/\tau_{cross}=1$. From 2.8 to 1.25 R_J, $\tau_{bounce}/\tau_{cross}$ decreases from 5.6 to 0.9. It is therefore not entirely clear whether the Alfvén wing model or the dc circuit model is the correct one. However, the Alfvén wing model results in the largest electric power if the comet is regarded as an electric generator in the ionospheric rest frame, which is the relevant rest frame here. We have therefore used that model in order to get upper estimates of these parameters.

Figure 5 shows the distance from the comet where $|E_{ext}|=|E_{\perp}|$ (the maximum radius where Eq. (10) can be used to find the electric field) along trajectory b. It is clear that this radius is much larger than the effective radius of the comet, which confirms the validity of the numerical model in that respect.

Figure 6 shows the total magnetic-field-aligned current from the comet (solid line) along trajectory b, as well as the total dissipated power (dashed line). At these orbit latitudes both the current and the power are basically inversely proportional to the distance from Jupiter. This is a consequence of the theoretical plasma density model by Divine and Garrett (1983). The maximum current, 6 kA, as well as the maximum power, 1800 kW, are both found when the comet is closest to Jupiter, 1.25 R_J in our calculations. Due to the very low ambient plasma density, the Alfvén velocity becomes $>c/2$ outside of 3.2 R_J, resulting in Eq. (10) no longer being valid. We have therefore not performed any calculations outside of that radius.

Figure 7 shows the field-aligned current density along trajectory b for a cross-section through the centre of the comet, perpendicular to v_{rel}. The upper panel shows the the current density close to the comet, while the lower panel shows the current density mapped down to Jupiter's ionosphere. The maximum current density close to the cometary nucleus is 3.9 $\mu A/m^2$ (55 $\mu A/m^2$ when mapped down to Jupiter's ionosphere). The cross section of the comet where the current density is of this order of magnitude is however very small, since according to Eq. (4) $j_{//}\propto 1/r_c^2$. The results for trajectory a are very similar, although the currents and electric fields are even smaller due to the higher latitude of that trajectory (see Figure 3).

Table I contains the data for trajectory b together with the corresponding data for trajectory a, for Io (Belcher, 1987), and for trajectory c which will be described below. In order to see what kind of measurable effects the currents will have it is natural to compare the results for trajectories a and b with the values for the Io flux tube. Io is located 5.9 Jovian radii from Jupiter and has an orbital velocity of 17 km•s^{-1}, 57 km•s^{-1} below the co-rotational speed of Jupiter's magnetosphere. The total current in the Io flux tube has been estimated to 3 MA, which is 500 times larger than the maximum current we obtain between comet Shoemaker-Levy 9 and Jupiter. However, because Io has a larger radius, the maximum current density close to Io is one order of magnitude lower than that close to the centre of

the cometary cloud; this difference in current density effectively disappears when the currents are mapped down to Jupiter. The main difference between the two cases is that, due partly to the difference in size, partly to the difference in ion mass injection rate, the induced electric potential difference across Io's flux tube in Jupiter's ionosphere is so much larger that the total dissipated power in the Jupiter-Io system is approximately a factor 10^6 larger than for Shoemaker-Levy 9. (One has to be a little bit careful when calculating the dissipated power in the Jupiter-Io system. The electric energy flux is not Lorentz-invariant when transforming from the comet's (or Io's) coordinate system to that of Jupiter. In the weak mass-loading case, the electric field as seen in Jupiter's rest frame will be $E_{\perp} \ll |v \times B|$, resulting in little dissipated electric power in Jupiter's ionosphere, while in the strong mass-loading case, the electric field in Jupiter's coordinate system is close to $-v \times B$. Using Eq. (11) it can be shown that Io injects more than twice as much ion mass to the Jovian magnetosphere during a time τ_{cross} as the Alfvén wave covers in the ambient magnetosphere during that time. Io is therefore a case of strong mass-loading, and the dissipated power in Jupiter's ionosphere is correctly estimated using $|E| = |v \times B|$.) Since this is the energy flux in the field-aligned current system, which is generally considered to be the source of the Jovian Decametric Radiation, the results of our calculations indicates that, irrespective of the emission mechanism, very little or no electromagnetic radiation of that sort caused by the comet's passage through Jupiter's magnetosphere will be detectable.

Trajectory c passes through Io's plasma torus, see Figure 3, and is intended to test the model by comparisons with the better-known Io-Jupiter system. For this trajectory $\tau_{bounce}/\tau_{cross} \gg 1$, and consequently the Alfvén wing model is the appropriate one, as it is for Io. Table I gives data for trajectory c at Io's plasma torus. The total field-aligned current is of the same order of magnitude as the current between Io and Jupiter, while, due to the difference in effective radius, the maximum field-aligned current densities are more than a factor 100 larger than those from Io. Figure 8 shows the total field-aligned current (solid line) and the total dissipated power (dashed line) along trajectory c. If the comet had followed this trajectory, we could possibly have expected a rather spectacular burst of decametric radiation. More important, the model gives a ratio between the injected ion mass from the comet and the injected ion mass from Io that is reasonably close to the ratio between the dissipated power from the comet and the dissipated power in the Jupiter-Io system. The total mass of the ions injected by the comet into the Jovian magnetosphere can be estimated using

$$\frac{dm_i}{dt} = m_i \int_{r_{c,min}}^{r_{c,max}} \frac{dn_i}{dt} 4\pi r_c^2 dr_c \tag{15}$$

This equation can be solved numerically. Using $r_{c,min} = 1$ km and $r_{c,max}$ equal to twice the effective radius of the comet which is 250 km inside the Io plasma torus (at 5.9 R_J), dm_i/dt becomes

approximately 2.5 kg$\cdot$s^{-1}, to be compared with 1000 kg$\cdot$s^{-1} for Io (Belcher, 1987). This shows that the physical assumptions behind the model are sound. The small electric power dissipated along trajectories a and b can thus be attributed entirely to the high latitude. (The results from trajectory c should be used with some caution, though. In Io's plasma torus, the maximum radius inside which Eq. (10) is valid is only half the effective radius of the comet. But since both the current density and the electric field decreases approximately as $1/r_c^2$, this should not change the basic conclusions.)

In most respects the results presented in this study represents an upper limit for the currents and power resulting from the electrodynamical interaction between comet Shoemaker-Levy 9 and Jupiter. However, the model of the Jovian magnetospheric plasma is quite uncertain along the comet's orbit, since the only available measurements have been performed close to the equatorial plane. It is also extremely difficult to predict the effects of more than 20 cometary nuclei passing through the Jovian magnetosphere one after each other. Clearly the passage of the first nuclei will cause disturbances to the magnetosphere. These disturbances could then possibly alter the the effects of subsequent nuclei.

Still, even considering such possibilities, the collision between comet Shoemaker-Levy 9 and Jupiter, can, from an electrodynamical point of view, probably best be summarized in the words of John Greenleaf Whittier (1807-1892):

"For all sad words of tongue and pen,
The saddest are these: 'It might have been!'".

Acknowledgements

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Table I

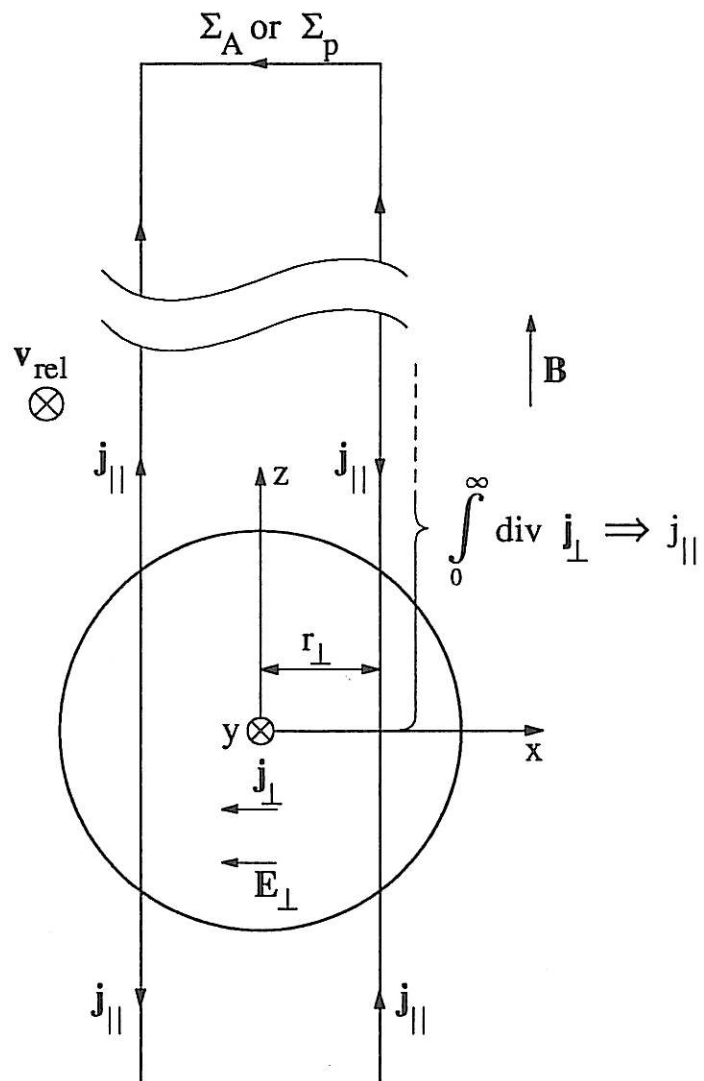|	Maximum current [A]	Maximum power [kW]	Maximum current density [μA/m^2]	Maximum current density in Jupiter's ionosphere [μA/m^2]
Trajectory a	$3 \cdot 10^3$	400	1.8	5
Trajectory b	$6 \cdot 10^3$	1800	3.9	55
Trajectory c, in Io's plasma torus	$1.2 \cdot 10^6$	$8 \cdot 10^6$	140	$44 \cdot 10^3$
Io	$3 \cdot 10^6$	$2 \cdot 10^9$	0.3	100

Fig. 1. The cloud model. The electric field is drawn in the comet's rest frame.
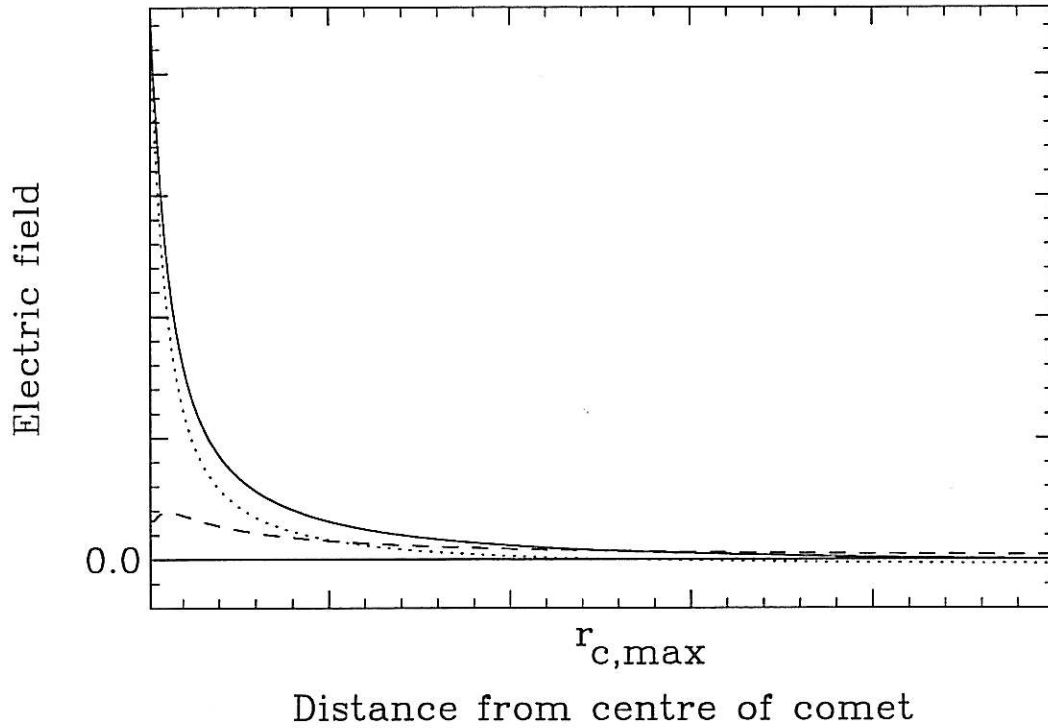
Fig. 2. The electric field perpendicular to v_{rel} caused by the displacement of the cometary ions relative to their corresponding electrons. The solid line shows the perpendicular electric field calculated from Eq.(10), the dashed line shows the external electric field calculated from Eq. (13), and the dotted line shows the total electric field. $r_{c,max}$ indicates the maximum radius of the cometary cloud inside which Eq. (10) is valid.
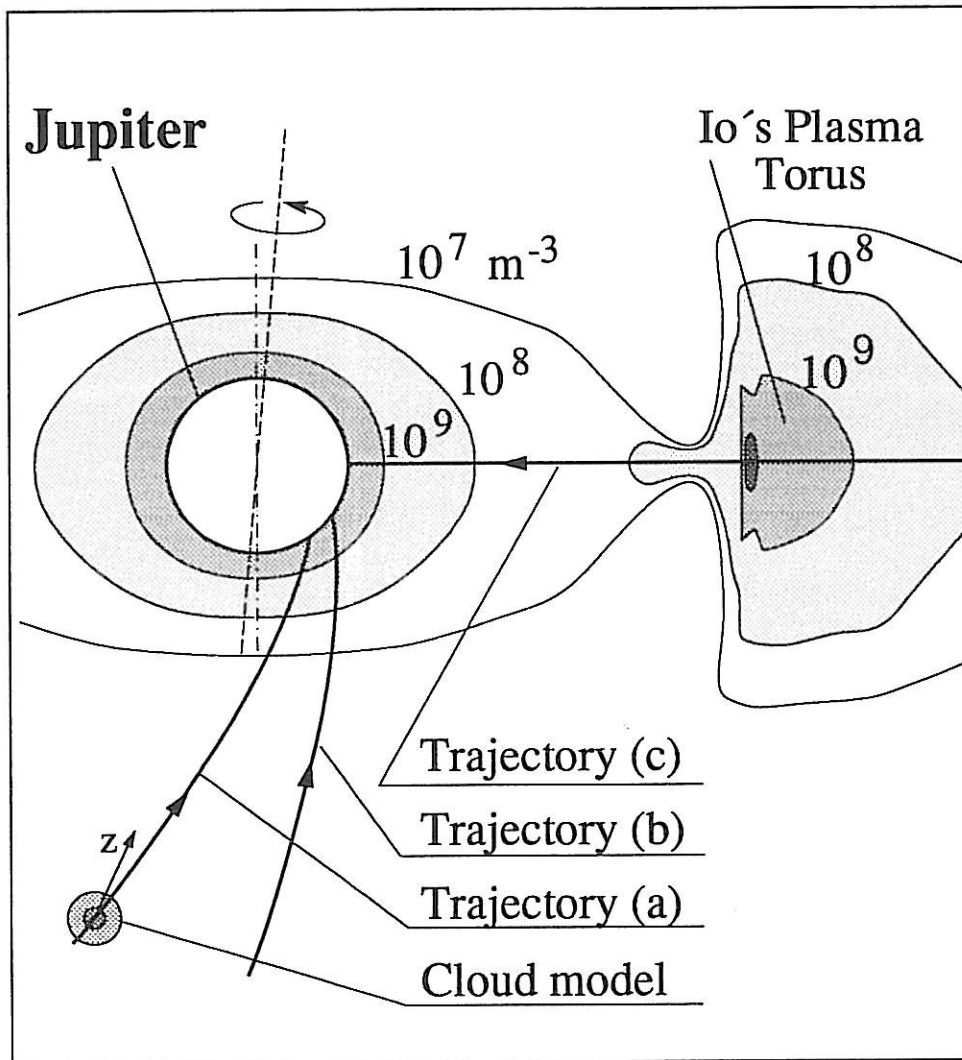
Fig. 3. Overview of the different comet trajectories which have been used in the calculations, and the Jovian magnetospheric plasma density. The trajectories (a) and (b) are intended to cover the variation in the orbit latitude of different cometary fragments with respect to Jupiter's centrifugal equator, while trajectory (c) is used to bench-mark the model against the Jupiter-Io interaction.
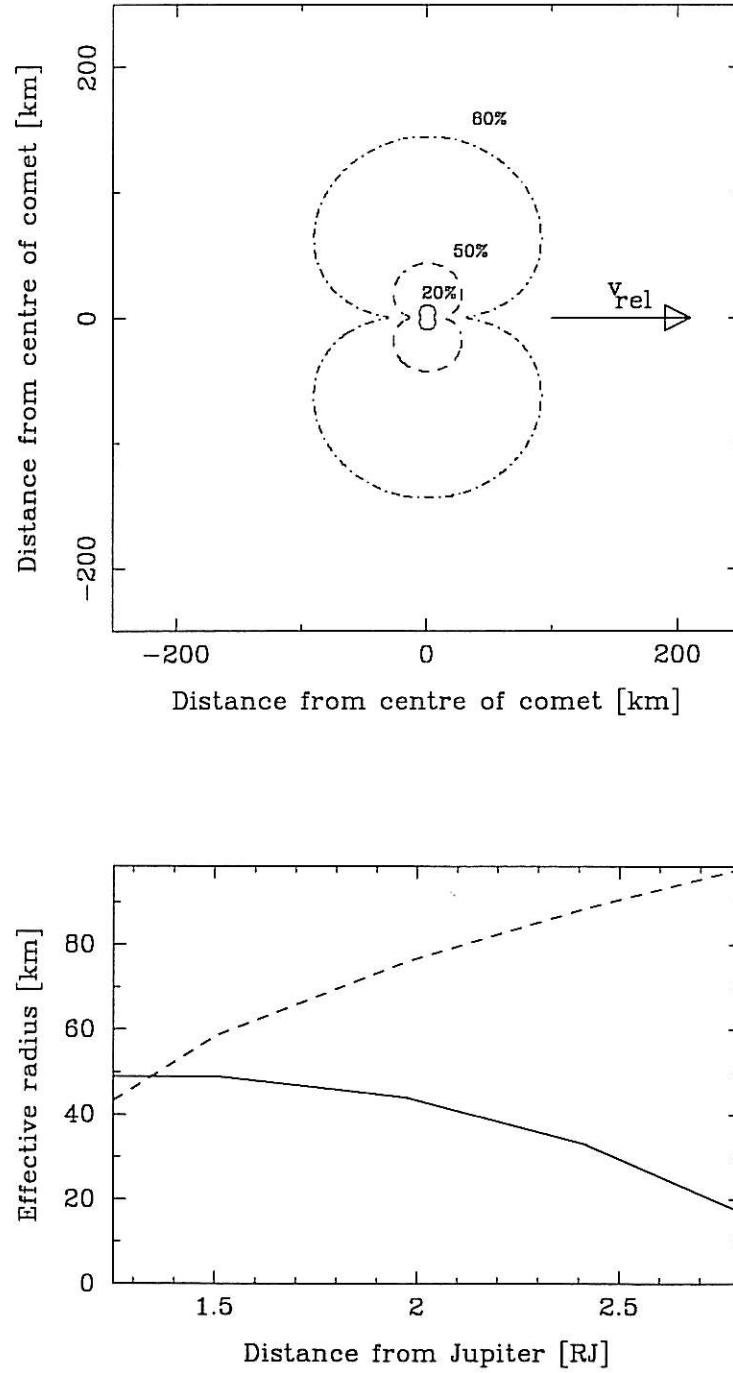
Fig. 4 upper panel. The distribution of the field-aligned current. A cross section over the flux tube close to the comet, with the comet's nucleus at 2 R_J.

Lower panel. The effective radius of the comet as a function of distance from Jupiter (solid line). Also shown is the theoretical effective radius where $\tau_{bounce}/\tau_{cross}=1$ (dashed line).
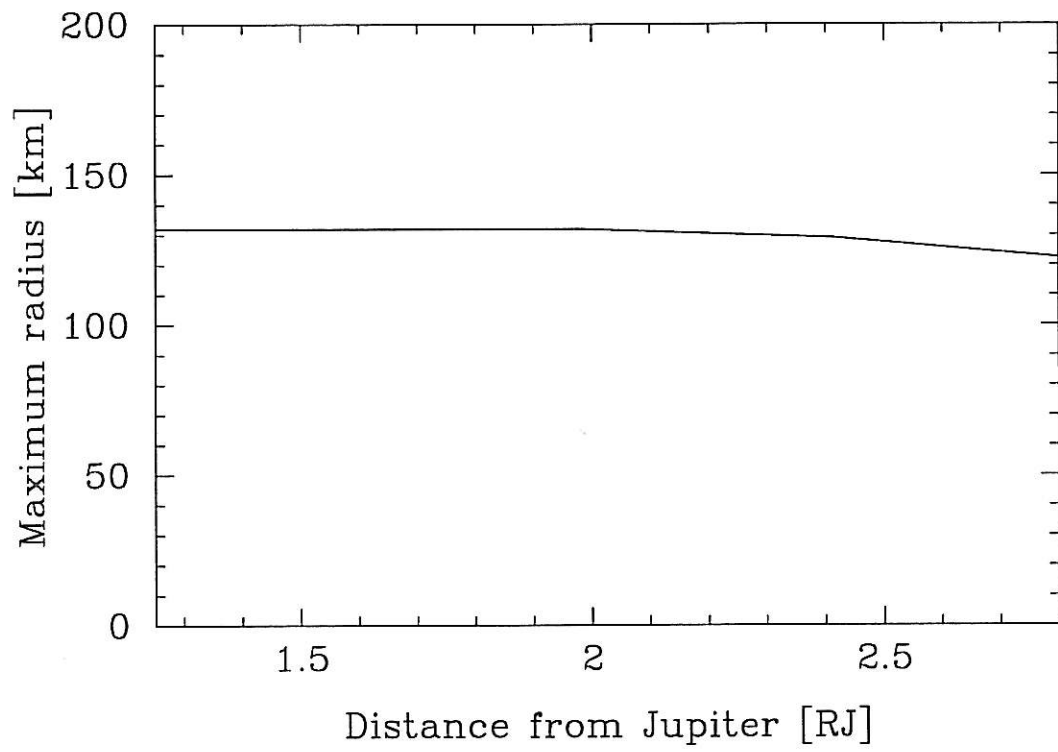
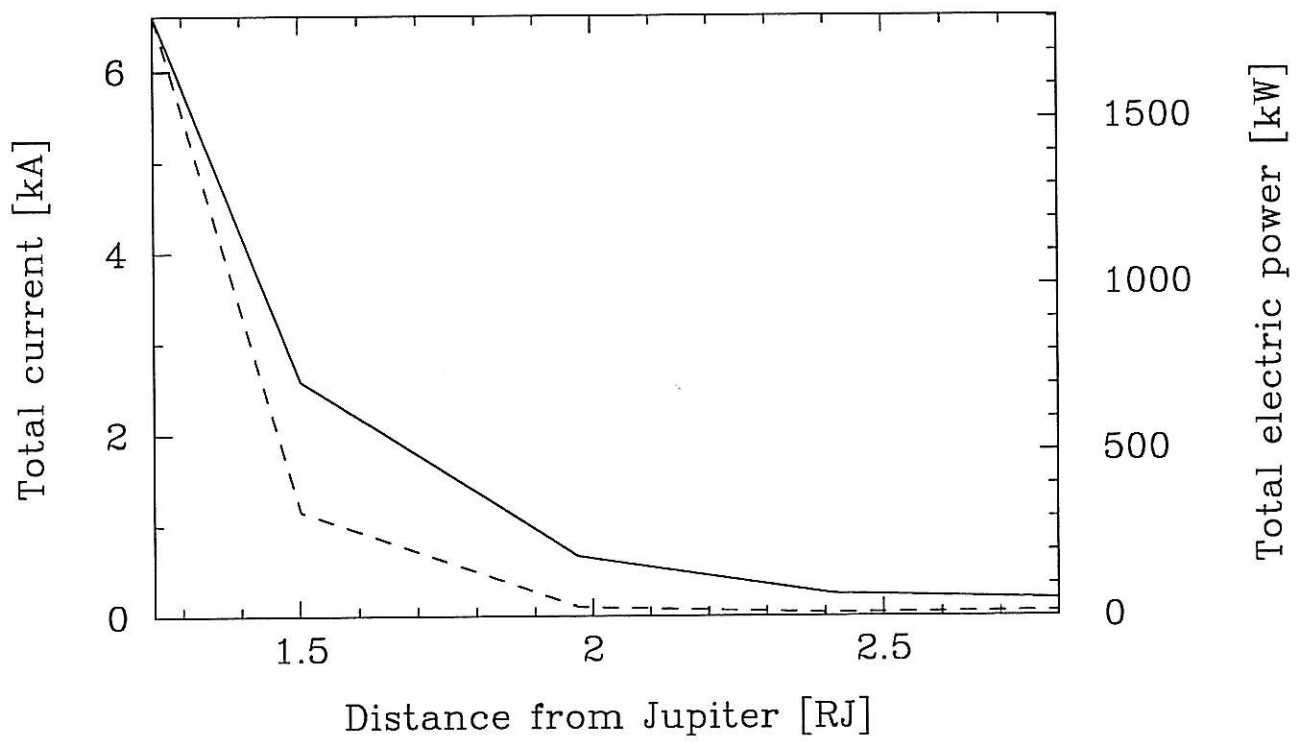Fig. 5. The maximum radius inside which Eq. (10) is valid to calculate the electric field, along trajectory b.

Fig. 6. Total current I (solid line) and power P (dashed line) as function of the distance from Jupiter, for trajectory b shown in Figure 1.
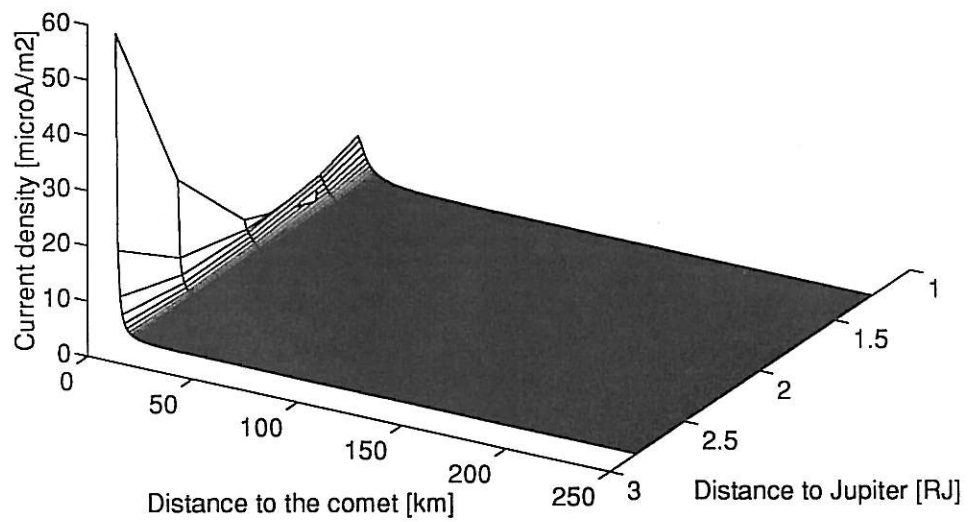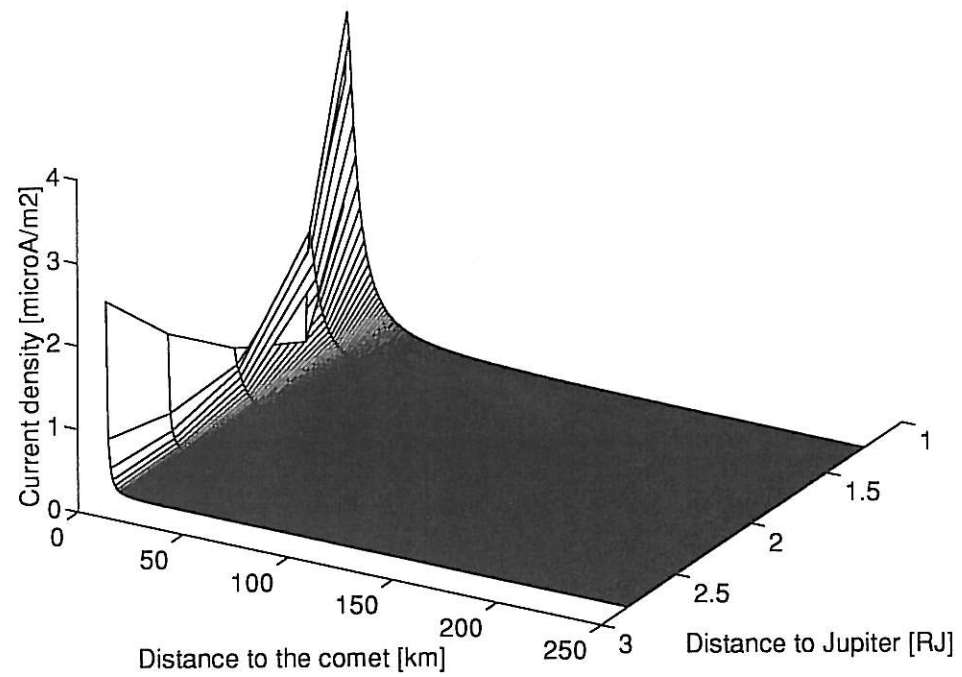
Fig. 7. Magnetic-field-aligned current densities along trajectory b close to the comet (upper panel), and mapped down to Jupiter's ionosphere (lower panel).
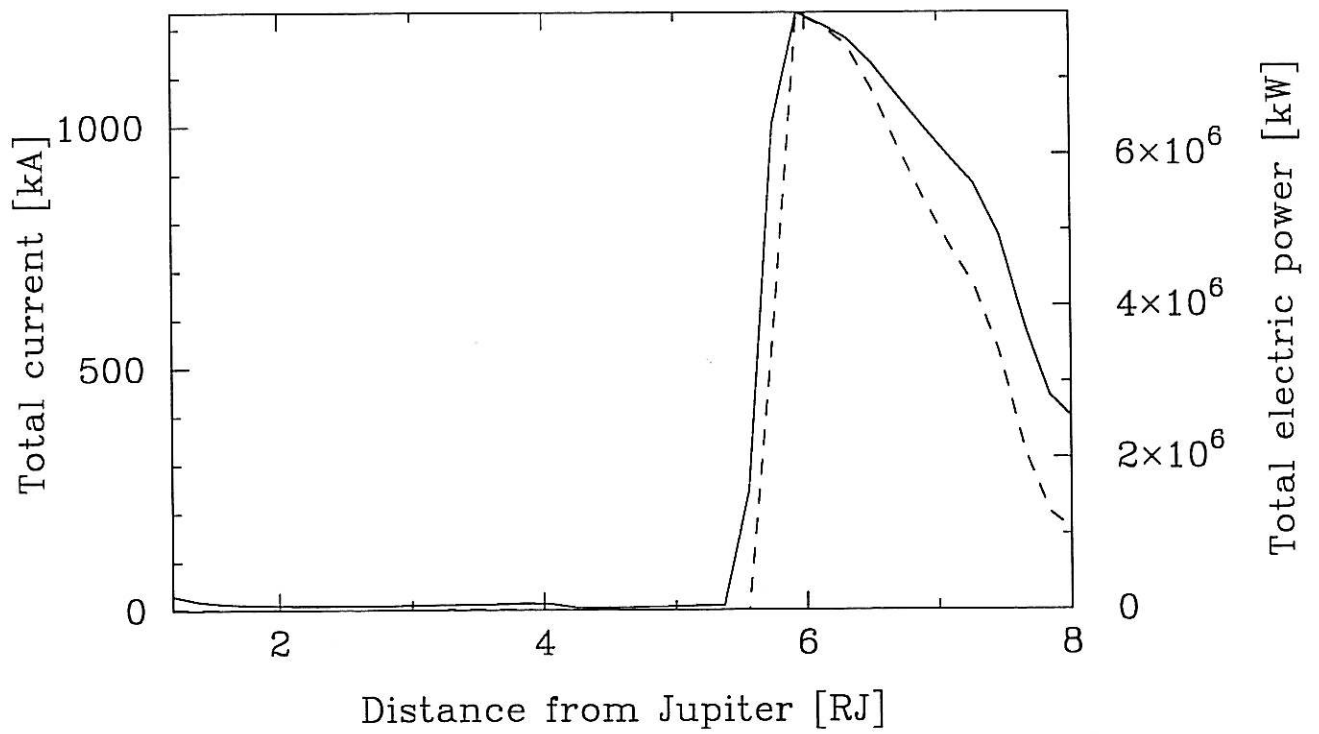
Fig. 8. Total current I (solid line) and power P (dashed line) as function of the distance from Jupiter, for trajectory c shown in Figure 3.

A NUMERICAL STUDY OF THE ELECTRODYNAMICAL INTERACTION BETWEEN COMET SHOEMAKER-LEVY 9 AND JUPITER'S MAGNETOSPHERE

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The electrodynamical interaction between Jupiter and comet Shoemaker-Levy 9, which is expected to impact on Jupiter around July 20, 1994, is investigated using a numerical model. The comet consists of a sequence of 21 or so nuclei, each surrounded by a neutral cloud of outgased material. A model is constructed of one single such cloud which is subject to electron impact ionization during the passage through Jupiter's magnetosphere. The cloud is assumed to couple electrically to the surroundings either by means of Alfvén wings analogous to the Jupiter-Io connection, or through a dc circuit that closes in Jupiter's ionosphere. The magnetic-field-aligned currents resulting from the Jupiter-Io interaction are strongly connected to the Jovian Decametric Radiation. The Shoemaker-Levy comet can theoretically supply ions to Jupiter's magnetosphere at a rate not so far below Io's, and will have a higher velocity relative to Jupiter, and could therefore conceivably drive similar processes. However, we find that, due to the high latitude trajectory of the comet, the resulting currents become very weak. The field-aligned currents obtained in this study are a factor 500 below those driven by Io, while the dissipated power is almost a factor of 10^6 below. It is therefore proposed that very little or no detectable electromagnetic radiation will arise during the comet's passage through Jupiter's magnetosphere.