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The plasma plumes of Europa and Callisto

Aharon Eviatar [a,*], Chris Paranicas [b]

[a] *Department of Geophysics and Planetary Sciences, The Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, 69978 Ramat Aviv, Israel*
[b] *The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD, USA*

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Abstract

We investigate the proposition that Europa and Callisto emit plasma plumes, i.e., a contiguous body of ionospheric plasma, extended in the direction of the corotation flow, analogous to the plume of smoke emitted in the downwind direction from a smokestack. Such plumes were seen by *Voyager* 1 to be emitted by Titan. We find support for this proposition in published data from *Galileo* Plasma Science and Plasma Wave observations taken in the corotation wakes of both moons and from magnetometer measurements reported from near the orbit of, but away from, Europa itself. This lends credence to the hypothesis that the plumes escaping from the ionospheres of Europa and Callisto are wrapped around Jupiter by corotation, survive against dispersion for a fairly long time and are convected radially by magnetospheric motions. We present simple models of plume acceleration and compare the plumes of the Europa and Callisto to the known plumes of Titan.

Keywords: Jupiter; Magnetosphere; Europa; Callisto; Satellites of Jupiter

1. Introduction

The icy Galilean satellites of Jupiter are surrounded by tenuous gaseous envelopes derived from their surfaces and thus can be said to possess atmospheres. The neutral atmospheres and ionospheres of Io (Kliore et al., 1974; Lellouch, 1996; Summers and Strobel, 1996) and Ganymede (Carlson et al., 1973; Kumar and Hunten, 1982; Hall et al., 1998; Eviatar et al., 2001b), inter alia, have been investigated in great detail on the basis of both *Voyager* and *Galileo* observations. The first hint of the tenuous neutral atmosphere of Europa, appeared in the Pioneer 10 ultraviolet observations of Wu et al. (1978). The existence of the atmosphere, which was predicted on the basis of laboratory experiments and theoretical considerations (Johnson et al., 1983; Eviatar et al., 1985), was only conclusively confirmed by *Hubble Space Telescope* ultraviolet observations in the mid-1990's, which indicated a column density in the range $(2.4 \times 10^{14}–2 \times 10^{15})$ cm^{-2} (Hall et al., 1995, 1998). The ionosphere was first detected by a *Galileo* radio occultation observation which showed an electron density near the surface of about 10^4 cm^{-3} with a mean scale height of about 350 km (Kliore et al., 1997).

A thin CO_2 atmosphere on Callisto was detected by means of the *Galileo* near-infrared imaging spectrometer (Carlson, 1999) and an ionosphere was found by the *Galileo* radio occultation experiment (Kliore et al., 2002) from which they inferred the existence of an atmosphere composed mainly of molecular oxygen. Attempts to observe ultraviolet emissions of O_2, CO, and CO_2 by means of the *Hubble Space Telescope* did not find airglow or aurora above an upper limit of 15 R (Strobel et al., 2002). Recent reviews of outer planet satellite atmospheres and ionospheres have been published by Gladstone et al. (2002) and Nagy and Cravens (2002).

The prototype satellite boasting a significant atmosphere is Titan, the large moon orbiting Saturn at a distance of 20 R_S. It was observed by the Plasma Science instrument

* Corresponding author.
E-mail addresses: arkee@daphne.tau.ac.il, arkee1@daphne.tau.ac.il (A. Eviatar).

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on *Voyager* 1 to emit a dense plume of cold ionosphere plasma that was wrapped by corotation around the magnetosphere several times before dissipating (Eviatar et al., 1982). In this study, we shall investigate the proposition that Europa and Callisto, despite the tenuous nature of their atmospheres, emit plasma plumes wrapped around the jovian magnetosphere. While we do not expect Europa and Callisto to emit such robust structures as seen near Titan, we entertain the hypothesis that plasma distinguishable from magnetosphere background and identifiable as being of ionospheric origin can be detected in organized, confined structures. For this purpose, we have perused the published data and conclude that indeed such plumes exists. We also model the atmosphere and ionosphere of Europa and Callisto in the light of observations.

2. Observations of plumes

In this section we shall review and summarize the observations that we interpret as indicative of the existence of satellite plasma plumes at both Europa and Callisto.

2.1. Europa

The characteristic signature of an ionospheric plume seen flowing out of Titan was a sharp increase in the electron density of about an order of magnitude above ambient and a corresponding plunge in the electron temperature (Eviatar et al., 1982). This is a result of the fact that ionosphere plasma is both dense and cold and ambient magnetosphere plasma is tenuous and hot. The *Galileo* orbiter encountered Europa several times and on four occasions flew through the geometrical corotation wake of the satellite. The orbits of *Galileo* in the vicinity of Europa are shown in Fig. 1. Signatures are seen in the PLS data published by Paterson et al. (1999) for encounter E4. The ion number density increased precipitously in the heart of the geometrical wake and at the same time, in contrast to the statement by Paterson et al. (1999) that the temperature rose at the time of the increase, the temperature dropped dramatically. It is also worthy of note that a few minutes earlier, just before the entrance into the geometrical wake, a smaller increase, having a double peak structure was associated with a milder decrease in temperature. We interpret these events as indications of a primary plume detected in the heart of the wake and a secondary plume appearing with reduced intensity after having been wrapped around the orbit by the rotation of Jupiter. The ultimate dispersal of satellite plumes under the effects of heating and plasma effects is discussed in detail by Eviatar et al. (1982). The displacement can be understood as a reflection of the centrifugal interchange motion of the magnetosphere flux tubes. At Saturn, the displacement of the plumes was attributed to the motion of the magnetopause since it corresponded well with solar wind data obtained by *Voyager* during its approach to the planet. Observations of jovian plumes away from the source satellite are discussed below.

Total electron density values, which represent the total plasma density, inferred from measurements made by the Plasma Wave (PWS) instrument were reported by Kurth et al. (2001) during the various encounters of *Galileo* with Europa. During the wake crossings, electron density enhancements were observed. On E4, the PLS results were well reproduced. During the E11 wake crossing, a density peak of 275 cm^{-3} was observed at 2050, in the wake, and was attributed by Kurth et al. (2001) to scavenging by corotating jovian plasma. The wave structure on the E15 wake crossing was highly complex and difficult to interpret, but there appears to be a Europa-associated peak of about 400 cm^{-3} at 2020. We interpret these electron density enhancements as signatures of plumes drawn off the ionosphere of Europa by the corotation electric field of the jovian magnetosphere.

Disturbances near Europa's orbit that are interpreted as the magnetic signature of a convected Europa plume were seen in the *Galileo* magnetometer data by Russell et al. (1999) on orbit G2. A pair of strong disturbances at 0900 and 1100 on September 7, 1996, when *Galileo* was at an L value of 11.2 are seen at conjugate distances (1.3 R_J) above and below the magnetic equator about 1.2 R_J outside the orbit of Europa. At the time of observation, *Galileo* was trailing Europa by about 45°. The geometry is shown in Fig. 2. Two weaker disturbances at 1430 (*Galileo* at $L = 11.2$) and 2200 (*Galileo* at $L = 10.9$) were also reported by Russell et al. (1999). These may well be the vestiges of older plumes emitted earlier by Europa and convected to *Galileo*. Southwood and Kivelson (1989) have shown that interchange modes of the type generated by the Io torus in the magnetosphere of Jupiter lead to convection rather than to the random walk type diffusion that characterizes the motion of the Titan plumes (Eviatar et al., 1982).

2.2. Callisto

Carlson (1999) observed a CO_2 atmosphere on Callisto with a column density of 4×10^{14} cm^{-2} for a temperature of 150 K, a scale height of 23 km and an inferred surface density of 8×10^8 cm^{-3}. There are indications of CO_2 in the ice surfaces of all icy satellites. Kliore et al. (2002) have observed a fairly dense ionosphere with electron profiles that show peak densities of 1.53×10^4 cm^{-3} at an altitude of 27.2 km (scale height 29.6 km) and 1.74×10^4 cm^{-3} at an altitude of 47.6 km (scale height 49.0 km). In accordance with the analogues of Europa and Ganymede, Kliore et al. (2002) infer a neutral O_2 column density of $(3–4) \times 10^{16}$ cm^{-2}, consistent with the observed density of the minor species CO_2. The results of Kliore et al. (2002) indicate that a necessary condition for the detection of a dense ionosphere plasma is solar illumination of the ram hemisphere during the encounter. The orbits of *Galileo* near Callisto are shown in Fig. 3.

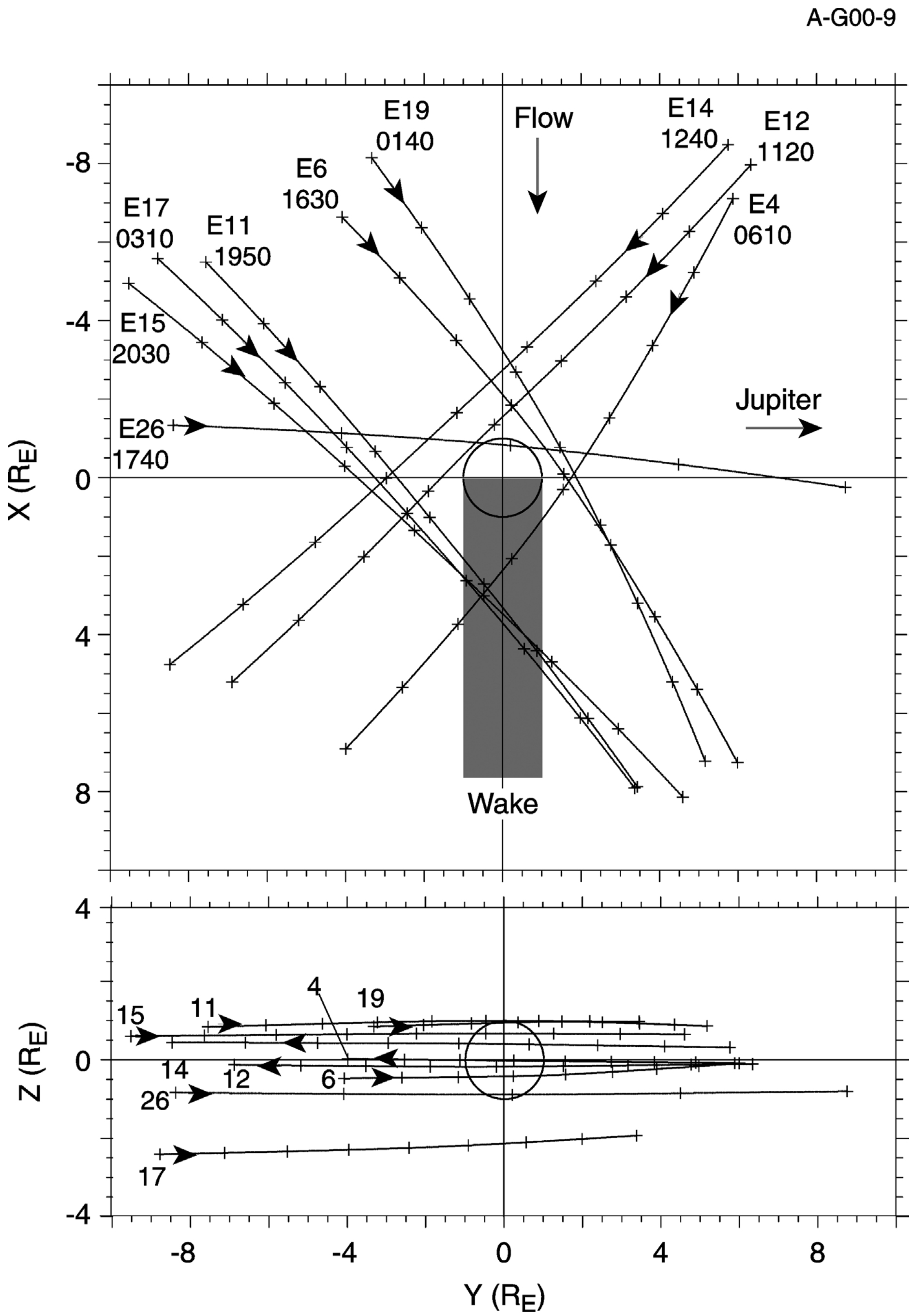

Fig. 1. Orbits of *Galileo* in the vicinity of Europa. The upper panel shows the projection into the plane defined by the corotation flow and the jovicentric radius vector and the lower panel shows the orbits in the vertical plane. The graphic was provided through the courtesy and generosity of W.S. Kurth.

Galileo PWS wave observations were made in the vicinity of Callisto by Gurnett et al. (1997, 2000) who found indications of plasma plumes on the C3 and C10 flybys but not on C22 although the ram hemisphere was illuminated and Kliore et al. (2002) detected a strong ionosphere signature on the inbound leg of that encounter. On the C10 encounter, a sharp maximum of about 400 cm^{-3}, nearly three orders of magnitude greater than ambient, was seen in the electron density near closest approach at an altitude of 535 km. C22 which showed, as mentioned above a robust ionosphere (Kliore et al., 2002), failed to display any sign of a plume at a distance of 2299 km downstream.

Comparison of the PWS and the radio occultation results tends to confirm the role of insolation in generation of the atmosphere. C22 was the only encounter from which data were published from both observations and the trailing hemisphere which was illuminated showed an ionosphere to the occultation, whereas the plasma wave experiment which crossed the wake in darkness failed to pick up a plume.

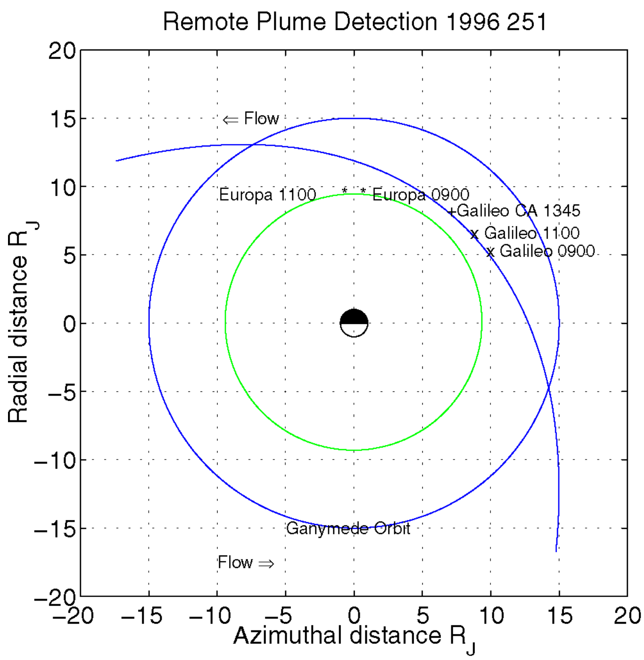

Fig. 2. Horizontal projection G2 orbit of *Galileo* at the time of the possible plume encounters reported by Russell et al. (1999).

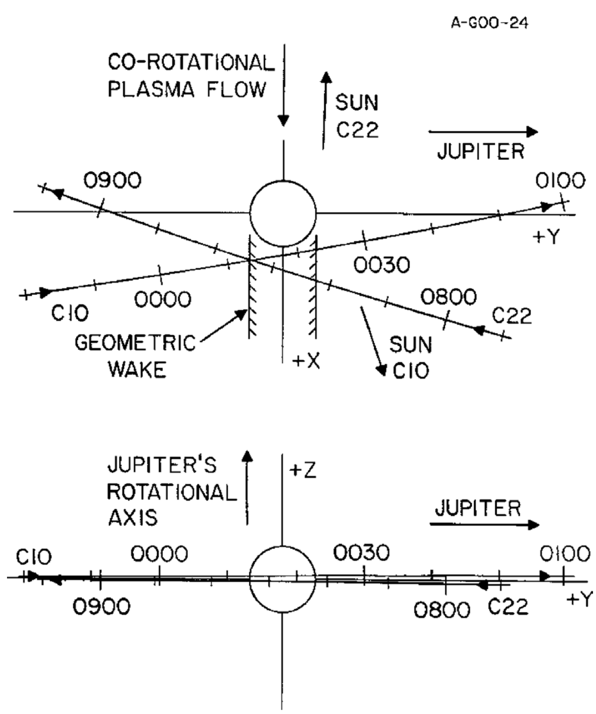

Fig. 3. Orbits of *Galileo* in the vicinity of Callisto. The upper panel shows the projection into the plane defined by the corotation flow and the jovicentric radius vector and the lower panel shows the orbits in the vertical plane. The graphic was provided through the courtesy and generosity of W.S. Kurth.

Encounter C9 which crossed a dark trailing hemisphere upstream saw no ionosphere. Encounters C2 and C10 which crossed a sunlit leading hemisphere showed strong electron density enhancements in the near downstream region. A search for plume signals around the orbit of Callisto appears to be a worthwhile endeavor.

3. Atmospheres and ionospheres

The tenuous atmospheres and ionospheres discovered by HST and *Galileo* observations are the source of the plumes described above at Europa and possibly at Callisto. A detailed aeronomic study of these atmospheres and ionospheres lies outside the scope of this paper. We shall, however, summarize some results from the literature and point out the incompleteness of the present state of understanding of the atmospheres.

In contrast to Ganymede the equatorial regions of which are shielded from the magnetospheric sputtering flux by an intrinsic magnetic field (Kivelson et al., 1998), the entire surfaces of both Europa and Callisto are exposed to energetic particles. Orton et al. (1996) observed Europa from *Galileo* and found a subsolar temperature of 128 K and a terminator temperature of about 90 K. Europa appears according to Orton et al. (1996) to exhibit a considerably lower thermal inertia than the other icy satellites and to be considerably colder on the night side than expected. Shematovich and Johnson (2001) have simulated the creation of the tenuous molecular oxygen atmosphere and show how it evolves from a near equilibrium configuration near the surface to a highly non-equilibrium atmosphere at higher altitudes. The global 3-D simulation of Saur et al. (1998) provides a satisfactory description of the neutral atmosphere in the equilibrium region near the surface, but becomes a poor approximation at higher altitudes. The observations of Hall et al. (1995, 1998) were not space-resolved on Europa and the satellite was taken to be a uniform emitting disk. They also derived their abundances from *Voyager* PWS electron data.

In view of these resolution limitations, we consider the atmosphere of Europa to be global and uniform, although, in reality, the composition of the atmosphere is latitude-dependent, since the polar cap temperatures, which are too low to allow effective sublimation, will cause any sputtered water vapor to recondense before it can dissociate. Molecular oxygen, on the other hand, can maintain a vapor pressure in the solid phase even at polar cap temperatures with the result that there will be gaseous O_2 available for interaction with the plasma, energetic particles and the solar UV flux (Johnson, 1996). In the low-latitude regions of Europa, the dayside temperature has been observed to be as high as 128 K (Orton et al., 1996) and a vapor pressure of water can be maintained above the ice. Bar-Nun et al. (1985) find that the sputtering yields of both water vapor and atomic hydrogen are temperature independent and of comparable magnitude which they interpret to imply that H is created by the breaking of water molecule bonds at the surface at a rate comparable with the sputtering of water. The hydrogen thus released will escape and the hydroxyl remaining behind will be photodissociated within a matter of days (Johnson and Quickenden, 1997), with the hydrogen again escaping. We expect, therefore, that there will be no detectable flux of protons in the escaping plasma plume, because of the fast escape in a time short compared to the ionization time, as was also shown with respect to the polar wind of Ganymede (Vasyliūnas and Eviatar, 2000; Eviatar et al., 2001b). For the case of Europa, the simulation of Shematovich and Johnson (2001) predicts an atmosphere dominated everywhere by O_2. A similar conclusion was reached with respect to both Europa and Ganymede from UV (Hall et al., 1995, 1998) and radio occultations (Kliore et al., 1997, 2002). In analogy with the analysis of Eviatar et al. (2001b) for an atmosphere over a sputtered ice surface, the dominant ion in the atmosphere is expected to be O_2^+. Atomic oxygen created by dissociative recombination of O_2^+ escapes and is, therefore, unavailable for local ionization by either electrons or UV photons.

A significant shortfall in the predicted model density was found for Europa by Shematovich and Johnson (2001) and it is clear that an additional source of sputtered matter is required, especially, as Shematovich and Johnson (2001) point out, the yield of molecular oxygen in the ion sputtering flux is no greater than 20%. Shematovich and Johnson (2001) suggest electron sputtering which while inefficient is capable of deep penetration and of bringing out molecular oxygen. Paranicas et al. (2001) estimate the energy flux of electrons into Europa to be of the order of $10^{11}\ \mathrm{keV\,cm^{-2}\,s^{-1}}$, which can provide a sufficiently large source strength of O_2, of order $2 \times 10^{10}\ \mathrm{cm^{-2}\,s^{-1}}$, if the G value (O_2 emitted per 100 eV of electron energy deposited) is as large as 0.02. Shematovich and Johnson (2001) used a somewhat lower estimate of the electron dose and found $G > 0.03$ to be the required constraint.

The situation at Callisto is even more complex and puzzling. The occultation data from *Galileo* cited above are consistent with a density about two orders of magnitude greater than that of Europa and Ganymede. Despite the resulting high column density no corresponding aurora or air glow emissions above an upper limit of 15 R were observed (Strobel et al., 2002), which deprives the model of the ultraviolet observational constraints on the densities available for Europa and Ganymede (Hall et al., 1995, 1998).

It is not immediately obvious why Callisto should have a denser atmosphere in view of the above mentioned fact that the particle energy flux available for sputtering delivered to Callisto and Ganymede's equator is about 300 times smaller than that delivered by Jupiter to Europa, while an intermediate flux is delivered to the polar cap of Ganymede (Cooper et al., 2001). As mentioned above, the detailed comparative aeronomy of the Galilean satellites lies outside the scope of this paper and is worthy of a separate study. We note that the paucity of available input energy can readily explain the absence of air glow emissions at Callisto. Aurorae at Ganymede are excited by the Birkeland current acceleration of electrons into the polar cap along the flux tubes of the intrinsic magnetic field (Eviatar et al., 2001a). No such mechanism capable of compensating for the reduced electron energy input exists at Callisto. It is thus to be expected that air glow and auroral UV emissions will be absent at Callisto without invoking a high conductivity ionosphere as proposed by Strobel et al. (2002). If indeed access to the surface of Callisto is denied by strong currents in the ionosphere, then it is not clear how a dense atmosphere and concomitant ionosphere can be created out of matter sputtered from the surface.

4. Acceleration of the plume

A major difference between the plumes of Europa and Callisto, and those of Titan, in addition to the density, is in the velocity of the plume. At Titan, *Voyager* 1 detected an outflow speed of about 10 km/s in the PLS data (Hartle et al., 1982) while the Low Energy Charged Particle (LECP) detector was unable to detect any flow in the wake of Titan (Maclennan et al., 1982). In the wake of Europa, on the other hand, the PLS measured velocity was at least 70% of the corotation velocity outside the wake (Paterson et al., 1999). Unfortunately, no information relating to the velocity of the plasma downstream of Callisto is available.

This difference between Europa and Titan is to be expected in view of the vast difference between the densities of the two atmospheres, the intensities of the interactions with the respective magnetospheres and the fundamental differences between Jupiter and Saturn. One such difference is the ability of the ionosphere of Jupiter to impose nearly rigid corotation, by means of its Pedersen conductivity, in the inner magnetosphere where the Galilean satellites orbit (Vasyliūnas, 1983), in contrast to the inability of that of Saturn to do so at the orbit of Titan. For the case of Titan, Eviatar et al. (1982) found that the only mechanism capable of accelerating ionosphere plasma to the observed velocity was a standing Alfvén wave configuration as modeled for Io by Neubauer (1980). Birkeland currents were found to be inadequate for the task.

It is shown in Eviatar et al. (1982) that the rate of acceleration by Birkeland currents of the plasma swept out of a satellite ionosphere is given by the expression:

$$\nu = \left(\frac{5}{2}\right)^{\frac{1}{2}} \frac{\Sigma_{\mathrm{p}} B_0^2}{H_m \rho c^2 L^6},$$

where Σ_{p} is the Pedersen conductivity in the planet ionosphere, B_0 is the surface equatorial magnetic field, ρ the ambient plasma density and H_m the scale height in the satellite ionosphere. For Titan where $L = 20$ and the conductivity is low, it is found that the plume cannot be accelerated in this manner. For Europa, located at much lower L and in the magnetosphere of a planet with a stronger magnetic field and a much larger Pedersen conductance in the ionosphere [as high as 0.5 mho (Hinson et al., 1998)], the acceleration rate will be much greater than at Titan.

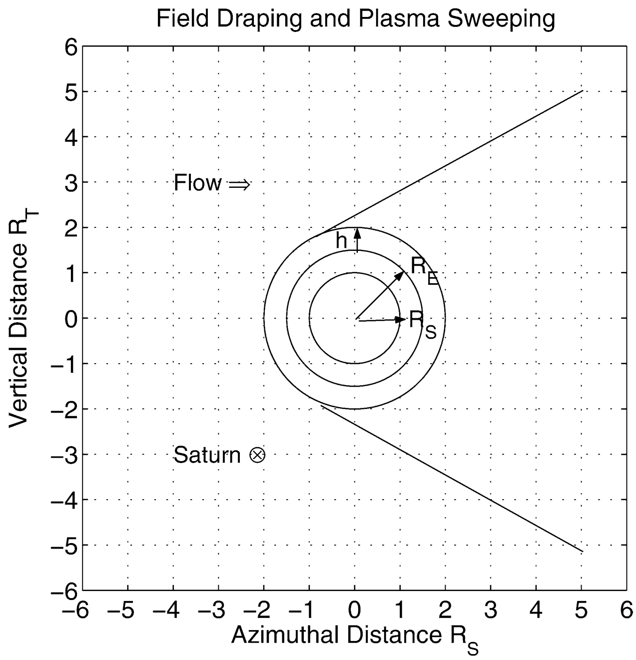

Fig. 4. A schematic representation of the draping of the corotating field around a satellite embedded in a magnetosphere and the sweeping of the plasma.

The acceleration by an Alfvén wave (Neubauer, 1980) is also significantly more effective for Europa than for Titan where it is shown to work (Eviatar et al., 1982). Consider the ponderomotive force exerted by the draping of the magnetic field around a satellite as shown in Fig. 4. The acceleration away from the satellite will take place in the region of the atmosphere in which the plasma density is fairly high but ion-neutral collisions can be ignored. The equation of motion is

$$\rho \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{J_r B_\theta}{c} \tag{1}$$

in which the effective current density can be estimated as

$$J_r = \sigma_\mathrm{A} \frac{VB}{c}\left(\frac{(R_\mathrm{E}+h)^2 - R_\mathrm{E}^2}{(R_\mathrm{E}+h)^2}\right) \approx \sigma_\mathrm{A} \frac{2h}{R_\mathrm{E}} \frac{VB}{c} \tag{2}$$

where the Alfvén conductivity is inversely proportional to the Alfvén velocity, i.e.

$$\sigma_\mathrm{A} = \frac{c^2}{4\pi V_\mathrm{A} R_\mathrm{E}}.$$

This enables us to write Eq. (1) in the form

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{2V_\mathrm{A} h V}{R_\mathrm{E}^2}. \tag{3}$$

The acceleration rate is proportional to the Alfvén velocity and this quantity will be significantly larger in the environment of Europa than in that of either Callisto or Titan because of the weaker magnetic field and lower ambient density at Callisto and Titan compared to these values at Europa. A comparison of the Alfvén velocities at the three satellites, for nominal parameter values is shown in Fig. 5.

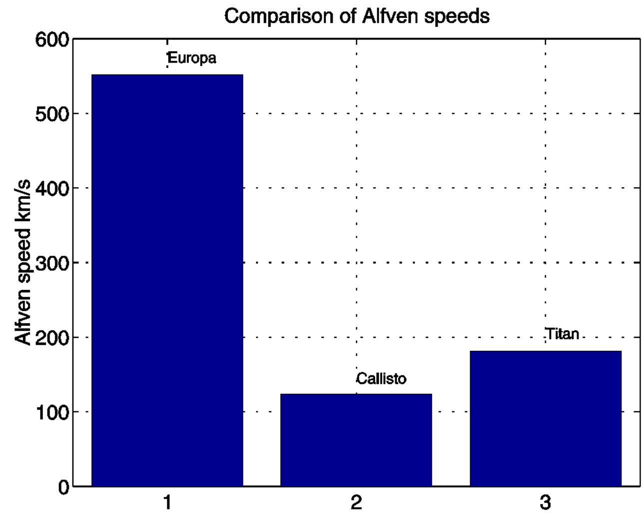

Fig. 5. Values of the Alfvén velocity at Europa, Callisto, and Titan.

5. Discussion

We have investigated the proposition that Europa and Callisto which have tenuous atmospheres and ionospheres and no magnetic field should exhibit the property of plume production in analogy to Titan, that has a much denser atmosphere. We have found evidence in the published *Galileo* findings for the existence of such plumes and have compared them to the corresponding phenomena at Titan. We conclude that the more rapid acceleration at Europa, compared to Titan, reflects the difference in local conditions, especially the Alfvén velocity, in the two magnetospheres.

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