Magnetospheric Ion Bombardment Profiles of Satellites:
Europa and Dione

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The spatial dependence across a satellite surface of the ion bombardment/implantation rate is calculated for satellites imbedded in planetary magnetospheric plasmas. These bombardment profiles are created by tracking ions in the plasma onto the surface of the object using an appropriate description of the ion motion. A parameter study is made indicating the general dependence on ion gyroradius and pitch angle. It is shown that access to the leading hemisphere depends strongly on the pitch angle distribution and that the gyromotion can cause differences in the bombardment of the inner and outer hemisphere. Profiles are then calculated for sulfur ions incident on Europa and oxygen ions incident on Dione using reasonable speed and pitch angle distributions. The results indicate that the longitudinal dependence of the UV absorption seen by Voyager closely follows the sulfur ion implantation profile at Europa if the hot plasma measured by LECP is not dominated by sulfur. This would appear to confirm that the feature is produced by ion bombardment. It is also found that for the assumed pitch angle distribution the dominant sputtering component at Dione bombards that surface nearly isotopically. This affects the analysis of the surface reflectance properties and the calculation of the heavy ion plasma source distribution. © 1989 Academic Press, Inc.

INTRODUCTION

Many satellites of the outer planets are exposed to magnetospheric ion bombardment (Cheng et al. 1986). This can induce chemical changes, cause erosion, or result in the accumulation of implanted particles in the surface. Certain aspects of the reflectance spectra of the icy satellites have been interpreted as being produced by these alterations (Burns and Matthews 1986). In this paper we examine the spatial distribution of the plasma ion bombardment of the satellites and relate this to observations at Europa and Dione.

A number of observations indicating the importance of the spatial distribution of the bombardment have been made. Morrison and Burns (1976) originally ascribed the well-known hemispherical asymmetry in the visible reflectance spectra of Europa to magnetospheric ion bombardment. A UV band observed on the trailing hemisphere of Europa was identified by Lane et al. (1981) as an SO band produced by implanted sulfur ions originating from the Io plasma torus. Clark et al. (1983) attributed spatial differences in the water ice IR band depth as being due to plasma bombardment (see also Clark et al. 1984, 1986).

The ion bombardment interpretation of the visible reflectance spectra was reinforced by the Voyager images of Europa (T. V. Johnson et al. 1983). The normal albedos in several bands obtained from the Voyager reflectance data of Europa (analyzed by Nelson et al. 1986) and their photometrically corrected versions (produced and analyzed by McEwen 1986) exhibit a minimum at the pole of the trailing hemisphere ($\theta = 0^\circ$) and the maximum at the pole of the leading hemisphere ($\theta = 180^\circ$). This dependence of albedos on the angle $\theta$ correlates with the maximum in the magne-
Fig. 1. Normalized flux of sulfur ions to the surface to Europa (left-hand axis) as a function of \( \cos \theta \), lower limit (cold ions, 100 eV or less); ---, upper estimate (90\% of the ion density as cold ions (\( \sim 100 \) eV) and 10\% of the ion density as hot ions (\( \sim 30 \) keV)) as estimated by Johnson et al. (1988a). Results of analysis presented in this paper: ----, 90\% of plasma density in the cold ions (\( \sim 100 \) eV) and 10\% of the plasma ion density in the hot ions (\( \sim 30 \) keV) combined as described in the text. Data points from Johnson et al. (1988a): ratio of the absorption coefficients, \( a_{UV} \), relative to the absorption coefficient at longer wavelengths, \( a_{OR} \). This comparison strongly suggests that the absorption is due to the plasma bombardment. However, these estimates were obtained based on several approximations (see Appendix). In particular the test particles were not correctly traced to the satellite surface and also the pitch angle distribution of the plasma, which allows access to the surface in the direction perpendicular to the overall ion flow (Sieveka and Johnson 1982), was not treated appropriately. For these reasons it is important to obtain distributions determined from reasonable plasma parameters.

The plasma torus at Saturn was shown by Pioneer (Frank et al. 1980) and Voyager (e.g., Richardson 1986) to contain heavy ions as well as protons. These heavy ions sputter the surfaces of the icy satellites (Lanzerotti et al. 1983) producing a cloud of neutral molecules (Cheng et al. 1986, Johnson et al. 1988b) which are ionized and swept up by the rotating magnetic fields. The newly created ions then become a component of the plasma ion torus and these in turn bombard the satellite surfaces. Therefore, the spatial distribution of ejected neutrals and spatial distribution of plasma in the torus are closely coupled (Johnson et al. 1988b). The spatial distribution of ejected neutrals is also dependent on the pattern of ion bombardment of satellite surfaces (Johnson et al. 1978b). As recent measurements of IR band depths by Clark et al. (1984) indicate that this bombardment is not isotropic, a detailed study of ion bombardment profiles of satellites is needed to correctly describe the heavy ion source distribution at Saturn.

In this paper we will discuss a general model of the magnetospheric ion bombardment (Sieveka and Johnson 1982), implying stronger absorption on the trailing hemisphere. The normal albedos for Europa extracted by McEwen (1986) were converted into single-particle albedos using the analysis of photon transport by Hapke (1981). The albedos were then used to estimate relative absorption coefficients (Johnson et al. 1988a). For comparison these authors also estimated the upper and lower estimates for the \( \theta \) distribution in the flux of sulfur ions to the surface of Europa using the hot and cold components of the plasma. Shown in Fig. 1 are the estimated limits, given as normalized fluxes (solid line is upper estimate, short-dashed line is lower limit), and the extracted UV absorption coefficient, \( a_{UV} \), relative to the absorption coefficient at longer wavelengths, \( a_{OR} \). This comparison strongly suggests that the absorption is due to the plasma bombardment. However, these estimates were obtained based on several approximations (see Appendix). In particular the test particles were not correctly traced to the satellite surface and also the pitch angle distribution of the plasma, which allows access to the surface in the direction perpendicular to the overall ion flow (Sieveka and Johnson 1982), was not treated appropriately. For these reasons it is important to obtain distributions determined from reasonable plasma parameters.
ment which can be applied to any satellite subject to such a bombardment. As pitch angle distribution will be taken into consideration, all possible plasma ion distributions can be described. We will show the patterns of ion–satellite absorption signatures and how, according to the plasma conditions, these patterns can change. Finally, we will describe the magnetospheric ion bombardment of Europa and Dione in order to clarify the observations discussed above.

CALCULATIONS

A rectangular system of coordinates, with its x-axis directed opposite to the lines of the magnetic field and with its z-axis directed according to the orbital motion of a satellite around the planet, was used in the calculations (Fig. 2). The satellite was assumed to have the same face (inner hemisphere) towards the planet, negative y direction, and therefore a fixed orientation in the field. Input data were: the radius of the satellite, R, the relative (with regard to satellite) velocity vector of the plasma rotation, \( \mathbf{v}_{\text{rot}} \), a mean ion speed, \( \bar{v} \), and the angular velocity of the ion motion, \( \omega \). All sample ions were traced from a point (starting point) of a circle (starting circle) with center in plane \( xy \) and radius equal to their gyroradius. Because of \( \mathbf{v}_{\text{rot}} \), they reached the satellite or not moving along spiral curves which are cycloids, as seen in Fig. 2.

The speed, \( v \), of an ion with respect to the field lines and pitch angle \( \alpha \) (angle between ion velocity vector and field lines) were selected by a Monte Carlo method according to a Maxwellian flux distribution (Bagenal et al. 1985) and an assumed pitch angle distribution, respectively. The total distribution function used was

\[
f(v, \alpha) \, dv \, d\alpha = \left( \frac{c}{\bar{v}} \right) \left( \frac{v}{\bar{v}} \right)^3 \exp \left( -v^2/\bar{v}^2 \right) \sin \alpha \, dv \, d\cos \alpha, \tag{1a}
\]

where \( c \) is a normalization constant and \( \bar{m} \bar{v}^2/2 = kT \). In the calculations for Europa and Dione the parameter for the pitch angle distribution, \( \gamma \), is not well established (Lanzerotti et al. 1981, L. J. Lanzerotti and A. F. Cheng, private communication) and somewhat different for hot and cold plasma. The selected values \( \bar{v} \) and \( \alpha \) were used to calculate the magnitudes of the components of the velocity vector \( v \) parallel (\( \bar{v}_|| \)) and perpendicular (\( \bar{v}_\perp \)) to the magnetic field lines. The latter, which causes circular motion, was used to calculate the ion gyroradius \( r = \bar{v}_\perp/\omega \) in Fig. 2. The above procedure was repeated a sufficient number of times to generate data for a required sample size. Note that when \( \gamma = 1 \) the average parallel velocity, \( \langle \bar{v} \cos \alpha \rangle \), is \( 0.65\bar{v} \) and the average perpendicular velocity, \( \langle \bar{v} \sin \alpha \rangle \), is \( 1.13\bar{v} \) with \( T_\parallel/T_\perp = \frac{2}{3} \); for \( \gamma = 2 \), \( T_\parallel/T_\perp = \frac{1}{2} \), and for an isotropic distribution, \( \gamma = 0 \), \( T_\parallel/T_\perp = 1 \).

The Voyager LECP data showed an ion spectrum which was harder than a Maxwellian velocity spectrum at large \( v \) (\( mv^2/2 \gtrsim 5kT \)). A flux distribution of the form (Krimigis et al. 1983)

\[
f(v, \alpha) \, dv \, d\alpha = \frac{c'}{v} \left( \frac{v}{\bar{v}} \right)^3 \sin \alpha \, dv \, d\cos \alpha \tag{1b}
\]

\[
[1 + (v^2/\bar{v}^2\kappa)]^{-(\kappa+1)} \sin \alpha \, dv \, d\cos \alpha
\]

Fig. 2. Geometry of the magnetospheric ion bombardment of a satellite. The northern hemisphere of the satellite is for \( x \rightarrow 0 \), outer hemisphere \( y \rightarrow 0 \). Typical path is shown from starting surface to satellite.
fits the data reasonably well. For large \( \kappa \) this reduces to the result in Eq. (1a). Typically \( \kappa \approx 4 \) (Krimigis et al. 1981, 1983). This changes the distribution in Eq. (1b) for ions with energies greater than \( \sim kBT \), at most 5% of the ions.

For the given set of values \( R, v_{\text{rot}}, v_{\parallel}, \) and \( r \), the area, \( Q \), of plane \( xy \) having the property that the ions with the center of their starting circle outside this area could not reach the satellite was determined. For each ion within the sample a starting point on a starting circle was chosen by selecting its center \( (x_0, y_0) \) from \( Q \) and a phase angle \( \beta \), as illustrated in Fig. 2. These were randomly chosen to complete a set of ion data. From this set of data the point of impact (or absence of it) for any ion of the sample was determined from the geometry of the problem. Then the flux of imparting particles was calculated for each "square" sector, \( a \) (1.5 \( \times \) 1.5 degrees), of the satellite surface. These were integrated over the satellite surface and scaled to unit total flux giving the relative fluxes \( \phi(a) \). For each set of plasma parameters there is an effective satellite surface area, \( A_{\text{eff}} \), for sweeping up the plasma. The total number of plasma ions per unit time striking satellite is obtained as \( n v_{\text{rot}} A_{\text{eff}} \phi(a) \). (2)

In order to understand the possible surface distributions for a given incident flux, the model described above was used in its full form and also with a number of simplifying assumptions. In the following we will describe and illustrate only that hemisphere of the satellite for which \( x \geq 0 \) (northern hemisphere) (see Fig. 2). There is a total symmetry of ion bombardment with regard to plane \( yz \), as the ions move up and down the field lines (two streams). A position on the northern hemisphere will be given by the angle \( \theta \), defined earlier, which varies from 0° (point \((0, 0, z_0 - R)\)) to 180° (point \((0, 0, z_0 + R)\)), and by the azimuthal angle about the axis of satellite motion, \( \psi \), which varies from 0° (point \((0, -R, 0)\)) to 180° (point \((0, R, 0)\)), as shown in Fig. 2.

**DISCUSSION: SIMPLIFIED CASES**

Input data \( R, v_{\text{rot}}, \omega, \) and \( \bar{v} \) are the significant parameters of the magnetospheric ion bombardment problem. Through Eq. (1a) or (1b) knowledge of \( \bar{v} \) is equivalent to knowledge of the set of \( v_{\parallel}, v_{\perp}, \) for each ion of a sample. In this section we will analyze simplified situations, for which \( v_{\parallel} \) and \( v_{\perp} \) are the same for all ions. In this case the set of significant parameters is \( R, v_{\text{rot}}, \omega, v_{\parallel}, \) and \( v_{\perp} \). Because the gyroradius is defined as \( r = v_{\perp}/\omega \), it is sufficient to discuss the pattern of the ion–satellite collisions as a

<table>
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<th>( \bar{v} ) (10^7 cm/sec)</th>
<th>( \gamma )</th>
<th>Distribution</th>
<th>( v_{\text{rot}} ) (10^7 cm/sec)</th>
<th>( \omega ) (rad/sec)</th>
<th>( A_{\text{eff}}/\pi R^2 )</th>
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<td>1b</td>
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</table>

\( ^{\text{a}} A_{\text{eff}} \) calculated here; \( R \) is satellite radius.
function of the ratios \((r/R)\) and \((\nu/\nu_{\text{rot}})\) in order to know the influence of these parameters.

If the perpendicular component of the ion velocity vector is ignored \((v_\perp = 0, r/R = 0, \text{ pitch angle equal to } 0^\circ)\) the particles would move along straight lines parallel to plane \(xz\) and with an angle to plane \(xy\) depending on the ratio \(\nu/\nu_{\text{rot}}\). This applies to ions originating at high magnetic latitudes and, of course, to the electrons, which are also known to modify the surface. The relative flux, averaged over all angles \(\psi\) and computed for different values of the ratio \(v/\nu_{\text{rot}}\) (0.1, 0.5, 1.0, and 2.0), is shown in Fig. 3a as a function of angle \(\theta\). It exhibits a cosine-like \(\theta\)-dependence with the maximum at the pole of the trailing hemisphere \((\theta = 0^\circ)\) and reaches zero for an angle \(\theta\) greater than 90°. Even though the particles move along the field lines there is depletion on the leading hemisphere as the ions are swept onto the trailing hemisphere by the motion of the satellite through the plasma (via \(\nu_{\text{rot}}\)). The linear motion of ions also causes a dependence of the ion impacts on the angle \(\psi\) with symmetry about \(\psi = 90^\circ\), as seen in Fig. 3b.

As the above results depend only on the ratio \(v/\nu_{\text{rot}}\), the numerical values shown may be taken as general.

If the parallel component of the ion velocity vector is ignored \((v_\parallel = 0, \text{ pitch angle equal to } 90^\circ)\), the ions would move in planes parallel to plane \(yz\) along cycloid curves of a shape depending on the ratio \(v_\perp/\nu_{\text{rot}}\) or, equivalently, \(\omega/\nu_{\text{rot}}\). This applies to ions freshly created in the satellite orbit planes at Jupiter and Saturn. In fact at Saturn, \(T_\parallel > T_\perp\) (Lazarus and McNutt 1983, Richardson and Eviaiar 1988). Any path is cycloid curtaile if \(v_\perp/\nu_{\text{rot}}\) is less than 1 or \(\omega/\nu_{\text{rot}}\) is less than \(1/r\), and is cycloid prolate otherwise. The relative flux averaged over \(\psi\) computed for a fixed value of \(\omega/\nu_{\text{rot}}\) and for different values of ratio \(r/R\) is shown in Fig. 4a. The relative flux again exhibits a cosine-like \(\theta\)-dependence with the maximum at the pole of the trailing hemisphere \((\theta = 0^\circ)\) and eventually becomes zero at some angle \(\theta\) greater than 90°. However, the directed circular motion of the ions causes a striking asymmetry in the \(\psi\)-dependence of ion impacts as seen in Fig. 4b. Increasing the gyroradius causes the asymmetry in the \(\psi\)-depenc-

![Fig. 3.](https://example.com/fig3.png)

Fig. 3. (a) \(\psi\)-averaged relative flux as a function of angle \(\theta\) in case \(v_\perp = 0; \ldots, \nu/\nu_{\text{rot}} = 0.1; \ldots, \nu/\nu_{\text{rot}} = 0.5; \ldots, \nu/\nu_{\text{rot}} = 1.0; \nu/\nu_{\text{rot}} = 2.0\). (b) Northern hemisphere profiles of ion-satellite impacts in case \(v_\perp = 0, \nu/\nu_{\text{rot}} = 2.0\) (8000 events).
dence to grow stronger. Therefore, such asymmetries should be expected when observing spatial variations in satellite reflectance spectra.

If an increase in $r/R$ occurs because $\omega$ or $R$ is decreasing, the numerical values of the distribution of impacts depend only on the ratio $v_\perp/v_{\text{rot}}$. But if an increase in $r/R$ occurs because $v_\perp$ is increasing, then the distribution depends on $\omega/v_{\text{rot}}$ and also on the satellite radius $R$. This occurs because the shape of the ion cycloid trace changes with respect to the shape of the satellite. The asymmetry in the $\psi$-dependence becomes more pronounced in the first case than in the second. Figures 4a and 4b illustrate the second case: increasing $v_\perp$, using parameters $R = 1.5 \times 10^8$ cm, $\omega/v_{\text{rot}}$ equal to $1.5 \times 10^{-7}$ rad/cm (both data for Europa), and $r/R$ equal to 0.1, 0.5, 1.0, and 2.0 in Fig. 4a. Because of the dependence on the satellite radius $R$, and on $\omega/v_{\text{rot}}$, the numerical values for these examples are not general. They do demonstrate, however, general trends.

In most of the cases examined above the ions predominantly bombard the trailing hemisphere of the satellite. Although increasing the gyroradius in Fig. 4a ($v_\parallel = 0$) does increase the access to the leading hemisphere, it is seen that even for $r/R = 2$ there are large leading/trailing differences. For $r$ fixed, lowering $v_\perp$ relative to $v_{\text{rot}}$ will increase the likelihood of bombardment on the leading hemisphere only for $\psi > 90^\circ$. However, a plasma ion component $v_\parallel \neq 0$, as in Fig. 3, can result in leading hemisphere impacts. Therefore, these calculations show that access to the leading hemisphere depends in a large part on the relation between $v_\parallel$ and $v_{\text{rot}}$, and not just on the gyroradius as is often stated.

Below we discuss the patterns of the magnetospheric ion bombardment for Europa and Dione. The patterns were obtained using the full model (described under Calculations) including appropriate distributions for $v$ and pitch angle.

RESULTS: EUROPA

Because mass analysis of the LECP instrument was not carried out near Europa,
the energy spectra appropriate for implantation of sulfur ions into the surface are very uncertain. Here we take two limiting cases. First, we assume $S^+$ is a minor component and use a temperature of $\sim 30$ keV (Krimigis et al. 1981) corresponding to the parameter $\tilde{\nu} = 4.2 \times 10^7$ cm/sec in Eq. (1b). We also use $\gamma = 1$ in Eq. (1b) (Lanzerotti et al. 1981, L. J. Lanzerotti and A. F. Cheng, private communication). This value of $\tilde{\nu}$ combined with the appropriate values of $R$, $v_{\text{rot}}$, and $\omega$ ($R = 1.5 \times 10^8$ cm, $v_{\text{rot}} = 1 \times 10^7$ cm/sec, $\omega = 1.5$ rad/sec) implies that the range $(0.09, 0.36)$ is most probable for ratio $r/R$, the range $(0.0, 5.7)$ is most probable for ratio $v_{||}/v_{\text{rot}}$, and cycloid traces of ions are very prolate ($v_{||}/v_{\text{rot}} \gg 1$).

The dashed line in Fig. 5a gives the calculated values of $\psi$-averaged relative flux of sulfur ions onto the surface of Europa as a function of $\theta$. It is seen that the small values of $r/R$ and the large values of $v_{||}/v_{\text{rot}}$ allow ions to reach almost all points on the satellite surface and result in a near linear $\theta$-dependence of the relative flux with the maximum $\sim 1.4$ at the pole of the trailing hemisphere ($\theta = 0^\circ$), and with the minimum 0.3 for $\theta = 180^\circ$. In Fig. 5b the large values of $v_{||}/v_{\text{rot}}$ and small values of $r/R$ cause a barely visible asymmetry in the $\psi$-dependence. However, the expectations of Sieveka and Johnson (1982) of significant changes in the $\theta$-dependence of ion impacts for different angles $\psi$ (for instance, $\psi = 0^\circ$ and $\psi = 90^\circ$) are not borne out. Using the results from Fig. 5b the dependence on $\theta$ for $0^\circ \leq \psi \leq 30^\circ$, $60^\circ \leq \psi \leq 120^\circ$, and $150^\circ \leq \psi \leq 180^\circ$ are all similar, although the larger $\psi$ exhibit larger fluxes. It is interesting that this similarity in the $\theta$ dependence is consistent with the findings of McEwen (1986) based on an analysis of the Voyager reflectance data, assuming the observed absorption is due to ion implantation bombardment.

For comparison to the above we take the other limit for the sulfur flux by assuming the measured LECP flux is dominated by sulfur ions. In this case a "temperature" of the order of 140 keV ($\tilde{\nu} = 9.2 \times 10^7$ cm/sec) is appropriate. Again assuming $\gamma = 1$ and using the expression in Eq. (1b), the $\psi$-averaged profile on the surface of Europa is given in Fig. 5a (solid line). It is seen that particles reach most regions of the surface nearly uniformly.

In addition to the hot plasma component there is a lower-temperature component of the Jovian magnetospheric plasma. At Europa we assume an effective temperature of the order of 1 keV ($\tilde{\nu} = 0.8 \times 10^7$ cm/sec) and $\gamma = 0$ in Eq. (1a). At this temperature the average values of both $v_{||}$ and $v_{\perp}$ are less than $v_{\text{rot}}$ and $R\omega$ (i.e., the range $(0.2, 0.6)$ is most probable for the ratio $r/R = v_{||}/R\omega$ and the range $(0.0, 0.7)$ is most probable for the ratio $v_{\perp}/v_{\text{rot}}$). Therefore this component of the plasma is predominantly swept onto the trailing hemisphere, giving very nearly a cosine $\theta$-dependence with almost no particles reaching the leading hemisphere for $\theta > 150^\circ$ (dotted line in Fig. 5a; viz., also ratios 0.1 in Figs. 3a and 4a). Changing the pitch angle to $\gamma = 2$ (dash-dot line in Fig. 5a) changes the distribution very little for these ions. The hemispherical profile for the first case is shown in Fig. 5c.

The lower limit (short-dashed curve) and upper estimate (solid curve) for the sulfur ion implantation flux at Europa, given by Johnson et al. (1988a), are shown in Fig. 1 presented as normalized fluxes. The lower limit is, roughly, a profile for the cold plasma component, just described. The upper estimate of flux was obtained (Johnson et al. 1988a) using an ion density which is a mixture of hot (1/10) and cold (9/10) sulfur ions. The hot plasma component was treated as a gas flowing onto all surface sectors according to the local relative velocity (Appendix), with an ion temperature of $\sim 30$ keV. No sweeping of the particles was considered, that is, the plasma filled in behind the satellite. These estimates for the sulfur ion component which is implanted were found to bracket the $\theta$-dependence of the relative UV (0.35 $\mu$m) absorption coefficient, $\alpha_{UV}$, extracted from the Voyager
Fig. 5. (a) $\psi$-averaged relative flux as a function of angle $\theta$: ••••• for cold sulfur ions at Europa ($\sim$1 keV) using Eq. (1a) and $\gamma = 0$; --- for cold sulfur ions at Europa ($\sim$1 keV using Eq. (1a) and $\gamma = 2$); —— for hot sulfur ions at Europa ($\sim$30 keV using Eq. (1b) and $\gamma = 1$); ---- for hot sulfur ions at Europa ($\sim$140 keV) using Eq. (1b) and $\gamma = 1$. (b) Northern hemisphere profile of ion–satellite impacts for Europa (8000 events) for hot sulfur ions ($\sim$30 keV, $\gamma = 1$, Eq. (1b)). (c) Northern hemisphere profile of ion–satellite impacts for Europa (8000 events) for cold sulfur ions ($\sim$1 keV, $\gamma = 0$, Eq. (1a)).

data (Johnson et al. 1988a) also shown in Fig. 1.

The flux profile calculated here by particle tracking for the hot plasma component ($\sim$30 keV) in which sulfur ions did not dominate the LECP data (Fig. 5a), was combined with the cold plasma result. These are combined using Eq. (2), the effective areas in Table I, and the relative number density given above. The result is indicated by the long-dashed line in Fig. 1. This allows a direct comparison to the $\theta$-depen-
dence of the extracted UV absorption coefficient.

It is seen in Fig. 1 that treating the hot plasma as a gas flowing onto the satellite fortuitously gave a reasonable result for the ion flux to the leading hemisphere for the Europa parameters (Johnson et al. 1988a) estimate. (As the magnetic axis is inclined about 10° to the satellite orbit axis, the calculated distributions should be smoothed somewhat.) It is also seen that the average variation with cos θ of the UV absorption coefficient is reasonably close to the ion bombardment profile calculated here. This strongly reaffirms that the ion bombardment causes the observed UV absorption. If the LECP data are treated as all sulfur then the number density of sulfur ions is much larger (A. F. Cheng, private communication) and the amount reaching the leading hemisphere (viz. Fig 5a for 140 keV ions) relative to that striking the trailing hemisphere would strongly disagree with the absorption coefficient unless burial of implanted sulfur was rapid (Sieveka and Johnson 1982).

RESULTS: DIONE

Saturn was observed to have a plasma torus containing oxygen ions which can be roughly characterized by two components with different temperatures (Frank et al. 1980, Krimigis et al. 1983, Richardson 1986). Therefore, for the case of Dione, parameters $\bar{v} = 4.9 \times 10^6$ cm/sec in Eq. (1a) and $\bar{v} = 4.9 \times 10^7$ cm/sec in Eq. (1b) for these two components of the heavy plasma and the appropriate values for $R$, $v_{rot}$, and $\omega$ ($R = 5.6 \times 10^7$ cm, $v_{rot} = 5.2 \times 10^6$ cm/sec, $\omega = 0.5$ rad/sec) were used. These describe the influence of a cold component of the plasma (~0.2 keV) and a hot component of the plasma (~20 keV), respectively. Again, for the LECP measurements mass discrimination was not available. The temperature used assumes protons dominate the hot component. If oxygen dominates then a temperature of ~80 keV is appropriate. Inside the orbit of Dione, $T_\perp/T_\| \sim 5$ (Richardson and Eviatar 1988, Richardson and Sittler 1988) for the cold component as the equilibration processes are slow (e.g., Cheng 1986, Johnson et al. 1988b). For the calculations at Dione we use $\gamma = 2$ ($T_\perp/T_\| \sim 2$) for both components and discuss the effect or changes in $\gamma$.

The first value of $\bar{v}$ indicates the range (0.1, 0.3) as most probable for $r/R$, the range (0.0, 0.9) as most probable for $v_\perp/v_{rot}$, and cycloid traces of ions are curate or prolate (ration $v_\perp/v_{rot}$ close to 1). The dotted curve in Fig. 6a indicates that $\psi$-averaged relative flux has a cosine-like $\theta$-dependence with the maximum ~3.0 at the pole of the trailing hemisphere ($\theta = 180^\circ$) which becomes zero for $\theta > 165^\circ$. It is also seen from the distribution of impacts for the cold plasma in Fig. 6b that the small values of $r/R$ and $v_\perp/v_{rot}$ produce a gentle asymmetry in $\psi$-dependence with more impacts at large $\psi$ when $\theta$ is large.

The parameter $\bar{v} = 4.9 \times 10^7$ cm/sec, which roughly describes a hot O$^+$ plasma if protons dominate the LECP measurements, implies that the range (1.0, 3.0) is most probable for $r/R$, the range (0.0, 9.0) is most probable for $v_\perp/v_{rot}$, and cycloid traces of ions are very prolate ($v_\perp/v_{rot} \gg 1$). The large values of $r/R$ and the very large values of $v_\perp/v_{rot}$ cause the $\theta$-dependence of the $\psi$-averaged relative flux to be very flat, as seen for the dashed curve in Fig. 6a. The maximum ~1.2 at the pole of the trailing hemisphere ($\theta = 180^\circ$) is close in value to the minimum ~0.8 at the pole of the leading hemisphere ($\theta = 0^\circ$), and there is almost uniform distribution of impacts. Increasing the temperature to ~90 keV ($\gamma = 1$, solid line in Fig. 6a) and/or reducing $\gamma$ merely assures the uniformity of particle impacts. The cold and hot components of the plasma surrounding Dione are seen to give very different bombardment distributions. Johnson et al. (1988b) have shown that the morphology of the cloud of neutral molecules which co-orbit with the satellites and, hence, the distribution of new heavy ions, is sensitive to the ion bombardment profile. As the
sputter ejection of H$_2$O is dominated by hot, heavy ions (Lanzerotti et al. 1983, Johnson et al. 1984), the calculations here indicate that the sputter source of neutrals used in these works is nearly isotropic assuming the parameters $\gamma$ and $\bar{v}$ are reasonable. An isotropic source (i.e., one for which the ejecta uniformly leave the surface of the satellite) results in a cloud of neutrals co-orbiting with the icy Saturnian satellites with a much larger radial extent than for a trailing hemisphere source (Johnson et al. 1988b). Therefore, the heavy ion source also is distributed in a similar manner with ions being created from icy satellite material well beyond the orbit of Rhea.

In addition to plasma production, modification of the surface reflectance properties is also attributed to plasma bombardment. Leading/trailing differences in the IR absorption signature of H$_2$O observed by Clark et al. (1984) have been attributed to differences in the bombardment rates. The differences in plasma bombardment rates result in different sputter erosion rates (e.g., Johnson et al. 1984) so that the average grain size on the two hemispheres is different. However, the ratio of fluxes for the hot component calculated here ($\sim 2/3$) does not appear to be sufficient to describe the observations. Therefore, the observed differences may be produced in some other manner by the low-temperature component of the heavy ion plasma or by the lighter H$^+$ ions, which are not the dominant sputtering components of the plasma. Alternatively, micrometeorites might contribute (Cheng et al. 1986) or the energetic plasma velocity distribution differs significantly from that assumed here, being more strongly peaked at large pitch angles (i.e., $\gamma$ larger), hence enhanced trailing hemisphere bombardment. Bombardment distributions, like those obtained here, must now be combined with a careful analysis of the types of textural changes responsible for the observed leading/trailing differences in order to describe the spatial dependence of the reflectance. It remains interesting and exciting that the reflectance and plasma observations can so closely constrain each other.
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CONCLUSION

We have calculated plasma impact profiles for satellites orbiting in planetary magnetospheres with fixed orientation to the field lines. By tracing ion trajectories, we first showed the effects of the various parameters on these profiles. In this it was made clear that small pitch angle is as important as large gyroradius if ions are to reach the leading hemisphere of a satellite. It was also shown that the gyromotion could lead to preferential inner hemisphere bombardment. We then calculated profiles at Europa and Dione using plasma ion velocity distributions which are thought to be reasonably representative of the Voyager data. The largest uncertainties are in the fraction of sulfur in the plasma at Europa and the appropriate pitch angle distributions. At Europa we created a sulfur ion implantation profile useful for evaluating the assumption that the leading/trailing differences in the visible reflectance and in the profile of the UV (0.35 µm) absorption extracted from Voyager data are due, at least in part, to the implantation of sulfur ions into the icy surface of Europa. The dependence on θ of the relative UV absorption coefficient extracted by Johnson et al. (1988a) is quite close to the implantation profile calculated here, strongly reenforcing the idea that this feature is produced by sulfur ion implantation. This agreement in the spatial distribution was based on the assumption that the LECP data were not dominated by sulfur, that the hot and cold ions affect the absorption equivalently, although their penetration depths differ, and burial of implanted species on the trailing hemisphere (Sieveka and Johnson 1982) is ignored. These ideas need to be further tested as laboratory confirmation of the UV feature has not yet been obtained (e.g., O'Shaughnessy et al. 1988). We also found that the bombardment flux computed for the parameters appropriate for Europa is not strongly ψ-dependent, consistent with the analysis of McEwen (1986).

At Dione we calculated profiles for the hot and cold components of the O+ plasma. These indicate that the hot plasma, which dominates the surface sputtering rate, bombards nearly isotropically for the plasma temperature and pitch angle distribution chosen. This affects the morphology of the heavy plasma ion source at Saturn (Johnson et al. 1988b). On the other hand, IR reflectance (Clark et al. 1983) suggests strong leading/trailing differences in the average grain size due to sputtering of the ice grains in the regolith. The analysis here would suggest that the differences observed must be due to some process other than sputtering, be produced by the colder and lighter ions (smaller gyroradii), or, more likely, be due to a pitch angle distribution for the hot component of the heavy ions which differs significantly from that assumed. Clearly, laboratory data on the effect of the ions on the reflectance spectra and the further analysis of the Voyager measurements of the hot component of the plasma are needed.

APPENDIX

Johnson et al. (1988a) estimated rough upper and lower bounds for the plasma flow onto Europa’s surface (solid and dashed curves in Fig. 1), treating the satellites as a sphere moving in a gas. If this gas is assumed to fill in behind the motion (i.e., sphere size compared to mean path of ions is ignored) then the flux is simply written

\[ \Phi = n_i \int [v - v_{\text{rot}}] \cdot (-\hat{n}) P(v) \, dv, \quad (A.1) \]

where \( \hat{n} \) is the local unit normal to the sphere, \( n_i \) is the ion number density, and \( P \) is the velocity distribution function. The integration is performed over positive values of the integrand only. As Johnson et al. (1988a) only showed the results, we give the expressions here from which the comparisons are made in Fig. 1 to our new results. They used, for simplicity, an isotropic Maxwellian function (\( \gamma = 0 \), in Eq. (1a)):
\[ P(v) \, d^3v \rightarrow 4\pi^{-1/2} \left(\frac{v^2\mu^3}{2}\right) \exp\left(-\frac{v^2\mu^3}{2}\right) \, dv. \]  
(A.2)

Substituting into Eq. (A.1) and integrating we obtain
\[
\Phi = n_i \, v_{\text{rot}} \cos \theta \, s(\pi/2 - \theta) 
+ \left(\frac{n\bar{\mu}}{4}\right) \exp(-\delta^2) \left[1 + 2\delta^2 \right. 
- 4\delta \int_{\delta}^{\infty} x^2 \exp(\delta^2 - x^2) \, dx], \]  
(A.3)

where \( \delta = v_{\text{rot}}/\bar{\mu} \) and \( s \) is the step function: \( s(x) = 1 \) for \( x > 0 \) and \( s(x) = 0 \) for \( x < 0 \). \( \delta \) is related to the ratios used in the text. In the limit \( \delta \gg 1 \) (cold plasma at Europa),
\[
\Phi = n_i \, v_{\text{rot}} \cos \theta \, s(\pi/2 - \theta), \]  
(A.4)

which gives a \( \cos \theta \) dependence on the trailing hemisphere only. For \( \delta \gg 1 \) (hot plasma at Europa),
\[
\Phi = (n_i v_{\text{rot}} \cos \theta/2) + \left(\frac{n\bar{\mu}}{4}\right). \]  
(A.5)

These two expressions were used to give the dashed and solid lines, respectively, in Fig. 1 as described in the text. They also give useful approximate bounds to the correct flux.

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