LABORATORY STUDIES OF CHARGED PARTICLE EROSION OF SO₂
ICE AND APPLICATIONS TO THE FROSTS OF IO

L. J. LANZEROTTI, W. L. BROWN, AND W. M. AUGUSTYNIAK
Bell Laboratories

R. E. JOHNSON
Department of Nuclear Engineering and Engineering Physics, University of Virginia

AND

T. P. ARMSTRONG
Department of Physics, University of Kansas

Received 1981 November 12; accepted 1982 February 22

ABSTRACT

The removal and/or redistribution of SO₂ frosts on the surface of the first Galilean satellite, Io, can occur through the erosion of these frosts by the magnetosphere particle environment of the satellite. We have studied in laboratory experiments the energy, species, and temperature dependence of the erosion rates of SO₂ ice films by charged particles. Rutherford backscattering and thin film techniques are used in the experiments. The ice temperature is varied between ~10 K and the sublimation temperature. The erosion rates are found to have a temperature-independent and a temperature-dependent regime and to be much greater, for 10–2000 keV ions, than those predicted by the usual sputtering process. The laboratory results are used together with measured magnetosphere particle fluxes in the vicinity of Io to estimate the erosion rates of SO₂ ice films from the satellite and implications therefrom on an SO₂ atmosphere on Io.

Subject headings: laboratory; spectra — particle acceleration — planets: Jupiter — planets: magnetospheres — planets: satellites

1. INTRODUCTION

Qualitative suggestions have been made that solar wind and magnetospheric plasma particles might alter the surface characteristics of planetary satellites (e.g., Mendis and Axford 1974) and, more specifically, might provide a production mechanism for the sodium and sulfur atoms associated with the Galilean satellite Io (Matson, Johnson, and Fanale 1974). These suggestions have begun to be placed on somewhat firmer grounds with our laboratory experiments on the erosion of frozen volatiles by charged particles (Brown et al. 1978, 1980 a, b) and the application of these results to icy bodies in the solar system (Lanzerotti et al. 1978a, b; Lanzerotti, Brown, and Johnson 1981; Cheng and Lanzerotti 1978; Johnson et al. 1981).

The discovery of the volcanism of Io (Morabito et al. 1979; Smith et al. 1979) provided an understanding of a source for the sulfur discovered in the cloud accompanying Io (Kupi, Mekler, and Eviatar 1976; Mekler and Eviatar 1978; Brown, 1981; Pilcher 1980; Pilcher and Morgan, 1980) and for the more energetic sulfur plasma in the Jovian magnetosphere (Krimigis et al. 1979a, b). While the molecules from volcanos may be ionized and thereby provide for some direct injection of sulfur into Jupiter's magnetosphere, the volcanic gases also appear to condense on the satellite surface, providing an SO₂ frost or adsorbate over regions that are not associated with volcanic hotspots (Bertaux and Belton 1979; Smythe, Nelson, and Nash 1979; Fanale et al. 1979; Nelson et al. 1980; Matson and Nash 1981).

The existence of an SO₂ condensed gas on Io has stimulated laboratory work to understand the reflectance spectra from the satellite (Slobodkin et al. 1980; Nelson et al. 1980) in order to better interpret Earth-based and Earth-orbiting observations of the satellite emissions, their temporal changes, and their possible relationship to a satellite atmosphere (Bertaux and Belton 1979; Butterworth et al. 1980). The possibility that the condensed SO₂ gas, in addition to subliming, could also be sputtered from the satellite surface, could contribute to the formation of an atmosphere and could produce an extended neutral cloud about Io (Smythe and McElroy 1977) requires laboratory-derived information on the erosion rates of SO₂ ices by magnetospheric particles. Such considerations have been presented previously for the ice-covered Galilean satellites (Europa, Ganymede, and Callisto) by Lanzerotti et al. (1978a) and Johnson et al. (1981).

Observational evidence suggests that SO₂ is condensed in significant quantities on various regions of Io's surface as a frost or an adsorbed species. The
surface is also believed to have exposed elemental sulfur as well as significant amounts of sodium and potassium. These latter elements are believed to be present because of the neutral sodium and potassium clouds observed at the orbit of Io (Brown 1974; Trafton 1975). Additional evidence for sulfur and oxygen on the surface of Io as \( \text{SO}_2 \) or other forms is the existence of an intense, primarily sulfur and oxygen, plasma coincident with the orbit of Io (Bridge et al. 1979) and more energetic sulfur and oxygen particles (Krimigis et al. 1979a, b; Hamilton et al. 1981). Models for Io’s surface composition vary from those which have significant fractions of the surface covered by \( \text{SO}_2 \) condensations as frost to those which have up to 60% coverage by elemental sulfur (Nash and Fanale 1977) and as little as 18% \( \text{SO}_2 \) frost coverage (Nash, Fanale, and Nelson 1980).

Recently Matson and Nash (1981) suggested that the surface of Io is very likely to be highly porous ( \( \sim 80\% - 90\% \) porosity). They contend that such a surface can provide a cold trap for gases produced by the volcanism. If so, significant amounts of \( \text{SO}_2 \) could be expected to be trapped in the surface and thus exposed to fast ion irradiation.

We report herein the results of laboratory measurements of the erosion rates of \( \text{SO}_2 \) ice by energetic particles. These experiments are part of a program of continuing laboratory studies of the erosion of frozen volatiles by charged particles, both for purposes of astrophysical research as well as for basic understanding of the physical processes involved. These laboratory results are used together with the fluxes of energetic ions measured by the Low Energy Charged Particle (LECP) instrument and the plasma science instrument on Voyager 1 to quantitatively determine the atmospheric and surface implications of charged particle impacts on the Io environment.

II. EXPERIMENT

We have used Rutherford backscattering and thin film techniques in our experiments. The experimental setup is shown in Figure 1. The targets are condensed gas films formed at low temperature on a beryllium substrate, upon which a 50Å marker layer of gold has been evaporated. The temperature of the cold finger can be varied from between \( \sim 10 \) and 200 K using a Cryotip (Air Products, Inc., Reading, Pennsylvania) helium transfer tube or can be maintained constant at liquid nitrogen temperature (77 K). The cold finger is surrounded by a liquid nitrogen cold can, inside of which is a grid (\(-1.3 \text{ kV}\)) for suppression of the emitted electrons in the erosion process. The cold finger can be rotated inside the cold can to face either an incoming Van de Graaff beam (0.5–2 MeV) or a low energy ion accelerator beam (6–50 KeV). Gas is condensed on the beryllium-gold substrate by admitting \( \text{SO}_2 \) (or other

![Fig. 1. Schematic illustration of experiment arrangement, including cold finger, copper cold can, gas manifold, annular solid state detector, and ion beams from Van de Graaff and electrostatic accelerators.](image)

gaseous) vapors as a broad stream through a tube which the cold surface is rotated to face.

A 1.5 MeV helium beam from the Van de Graaff accelerator is used as the analysis beam for measuring the progression of erosion of a condensed gas film by other ion species from either accelerator. (The 1.5 MeV helium beam can also be used for erosion, of course.) In the course of an experiment, a given exposure dosage of the film to the eroding ion species is followed by a given exposure dosage of the analysis beam. For convenience the erosion dosage is generally selected so as to obtain erosion of about one-half or more of the film in four or five doses. Corrections as required are made in the analysis for erosion during the analysis exposures.

The backscattered helium analysis ions are detected in an annular solid state detector (Fig. 1). The spectra of backscattered 1.5 MeV helium ions from an \( \text{SO}_2 \) ice film at three different stages in the erosion of the film, in this case also by 1.5 MeV helium ions, is shown in Figure 2. The molecular thickness of the \( \text{SO}_2 \) film can be deduced from such backscattering spectra, both from the number of counts in the individual sulfur and oxygen backscatter peaks as well as from the shift of the centroid of the gold marker peak. The overall gain of the system is monitored throughout the measurement by use of a pulser set slightly higher in energy than the centroid of the gold backscattering peak. Comparisons of the erosion rate under energetic ion bombardment as given by the three separate measures allows a determination of any change in the average stoichiometry of the film. For the erosion of the \( \text{SO}_2 \) condensed gas films, no measurable change in film stoichiometry was observed.
Fig. 2.—1.5 MeV He⁺ backscatter spectra for three different incident total fluences on the sample at 77 K. The energies of the helium beam backscattered from the surfaces of the SO₃ sample and the gold film are shown.

In Figure 2, note that the number of counts in each of the oxygen and sulfur backscattering peaks decreases as the incident dosage of helium eroding ions increases. The decrease in counts is seen both from the total peak counts as well as from the movement forward of the lower energy edge of each of the peaks, showing that the film thickness is decreasing. The high-energy edges of the sulfur and oxygen peaks remain stationary, because the edges correspond to backscattering from the front surface of the film. The oxygen and sulfur marks at 0.54 MeV and 0.91 MeV, respectively, indicate the energies of these backscattered helium ions.

The erosion of the film is also evident from the movement of the centroid of the gold marker to higher energies as the thickness of the overlying SO₃ film decreases. The mark at 1.38 MeV on the gold centroid indicates the energy of backscattered 1.5 MeV helium from the outer surface of the bare gold film. The shape of the gold centroid peak indicates that the condensed gas layer was basically uniform initially and remained that way during the erosion process. (Significant non-uniformities in the erosion of water ice films have been reported by Brown et al. 1978, 1980a). The measurements of SO₃ ice erosion were all made on films of \((3-4) \times 10^{17}\) molecules cm⁻² thickness.

Measurements of the erosion of an SO₃ film were made using incident 0.75 MeV and 50 keV hydrogen ions as well as 1.5 MeV hydrogen molecules, helium, oxygen, and argon ions. The erosion yields for these ions at low (\(\sim 10\) K) temperatures are plotted in Figure 3 as a function of the electronic energy loss per unit path.
length in SO₂ gas \( (dE/dx) \) divided by the number density \( N \). The condensed gas film is treated to a good approximation, as a very dense gas and atomic stopping powers for sulfur and oxygen are combined (Anderson and Ziegler 1977; Ziegler 1977; Lindhard and Scharff 1961). The line drawn through the hydrogen and helium points is proportional to the energy loss squared. This relationship is the same as that found for hydrogen and helium sputtering of H₂O ice films (Brown et al. 1980a, b). Such a relationship allows one to estimate the yields at other incident ion energies. The heavy ion (oxygen and argon) low temperature erosion rates are substantially higher than would be predicted by the \((dE/dX)^2\) relationship for the hydrogen and helium, which is also similar to the situation found for heavy ion sputtering of water ice (Brown et al. 1980a; Seiberling et al. 1982).

We have previously shown that the sputtering yield for H₂O films has a temperature independent regime at low temperatures as well as a thermally sensitive regime. In the latter regime the erosion rate appeared to depend linearly on the incident ion energy loss (Brown et al. 1980b). In order to describe the erosion of SO₂ on Io, we investigated the temperature dependence of the erosion rate using both hydrogen and helium ions. These data are important as the temperature on the surface of Io may vary considerably because of diurnal heating and local volcanism. Indeed, evidence has been presented from both Voyager and ground-based infrared measurements that hot spots can exist on the satellite (Huncl et al. 1979; Sinton et al. 1980). Shown in Figure 4 are the experimentally determined sulfur dioxide yields as a function of temperature. These yields are seen to be temperature independent from the lowest temperatures measured (approximately 10 K) to approximately 60 K. At higher temperatures, the yield can be represented reasonably well by an exponential function of the film temperature. This temperature increase is believed to be, like that observed in water, associated with a diffusion process in the ice (Brown et al. 1980b; Johnson and Brown 1982).

III. MECHANISMS

As for the water ice measurements reported by our group (Brown et al. 1978, 1980a, b), the erosion rates determined in these experiments on SO₂ ice are also much larger for these ions and energies than would be predicted on the basis of classical sputtering theory (Sigmund 1969). We note that, qualitatively, charge repulsion along the ionized track produced in the material would give the power law dependence on stopping power that is observed in H₂O and now SO₂ films for incident H⁺ and He⁺ ions (Haff 1976; Stiegler and Noggle 1967; Brown et al. 1980a, b; Johnson and Brown 1982). That is, along the path of an incident ion, electrons (from ionization of the molecules in the path) will be deposited, on the average, at larger radii from the incident particle track than the positive ions from which they were removed. If the electrons are relatively immobile, by being trapped at their deposition radii, a cylindrical space charge region will result which exerts strong forces on the ions in the direction of the normal to the film surface, at which the space charge region terminates.

The same power-law dependence is obtained if a hot, narrow, cylindrical thermal spike is created along the incident ion path with the input thermal energy proportional to \( dE/dx \) (Vineyard 1976; Johnson and Evatt 1980). The means of conversion of the electronic energy into thermal motion in such a model is uncertain. However, if the electrons are mobile, recombination and decay of the electron-ion plasma along the track may create a heated region. For ions depositing a very high energy density (e.g., heavy ions such as Ar⁺ and O⁺), the ion repulsion discussed above may produce a thermalized region, in which case the dependence on energy loss would be expected to be steeper than \((dE/dx)^2\) (Seiberling et al. 1980). These mechanisms and others are discussed in more detail elsewhere (Brown et al. 1982; Johnson and Brown 1982; Haff 1982).

Of more usefulness to astronomical research than the parameterization shown in Figure 3 is a plot of the SO₂ yield as a function of the impacting particle energy for the low temperature erosion. The energy loss-squared dependence for hydrogen and helium can be used with reasonable confidence to plot the erosion rate as a function of incident ion energy, as shown in Figure 5. Also shown are the yields from the collision cascade sputtering process calculated based on an adaptation of the model of Sigmund (1969) for the sputtering of metals. The yields for fast sulfur and oxygen are obtained by assuming that the heavy ion yields agree with the light ion yields at low \( dE/dx \), an assumption.
which should underestimate the heavy ion yields. This figure shows very strikingly the large enhancements of the yields at ion energies $\geq 10 \text{ keV}$ over those expected from the collision cascade process, a characteristic of the sputtering of insulators (Brown et al. 1981; Seiberling et al. 1982; Ollerhead et al. 1980). In fact, the largest electronic yields are also larger, by a factor of about 10 or greater, than the largest yields expected from collision cascade sputtering.

We caution that the low-velocity yields, particularly for the larger ions, may have a dominant thermal spike contribution produced by elastic collisions; these yields may be larger than the cascade yield shown, as the material binding energy is small. Such an effect has been observed in metals (Sigmund and Clausen 1981), but it is an unexplored phenomenon in the erosion of frost. The velocity distribution of the eroded species from such a thermal process is likely to be lower than for particles emitted by the collision cascade process.

**IV. APPLICATIONS TO IO**

We can now apply these laboratory results to the erosion of the surface of Io. We have used the measurements from the Low Energy Charged Particle (LECP) experiment and the Plasma Science (PLS) experiment on Voyager 1 to estimate the particle fluxes. The LECP instrument provides measurements in the energy range where the electronic processes are most important for the erosion. Unfortunately, in the most intense parts of the Jovian radiation field, which occurs near Io, the LECP instrument was not able to provide data at the lowest energies of its capability ($\sim 23 \text{ keV}$ for hydrogen) because of saturation effects from the very intense radiation. In addition, the ion particle fluxes are found to decrease substantially around the orbit of Io (Krimigis et al. 1979a) with the spatial distribution of the decrease dependent upon ion energy. The decreases observed in the low energy ion fluxes in the vicinity of Io have been attributed to charge exchange scattering of the ions with atoms in the Io torus (Lanzerotti et al. 1981).

Shown in Figure 6 are spectra from LECP as a function of energy for several different Jovian radii, ranging from near Europa ($\sim 9 R_J$) to the location of Io ($\sim 6 R_J$). These spectra are plotted as if the measured ions were all hydrogen. The composition is not known, however, as the LECP composition detector system was turned off prior to the encounter with Io because of saturation effects. The spectra of Figure 6 show clearly that the low-energy rollover in the spectra seen at greater distances from Jupiter (e.g., Krimigis et al. 1979a, b) tends to disappear with the approach to Io and shows a decrease in the intensity. The dashed line at $R_J = 6$ is based on an interpolation using the data shown at 7.1, 6.6, and 5.6 $R_J$. Below 150 keV, a nearly constant flux with energy is assumed.

The fast-ion spectrum at 6 $R_J$ is plotted in Figure 7, together with the extrapolation of the PLS measure-

---

**Fig. 5.**—Erosion yield as a function of incident ion energy for four ion species. Dashed lines: contributions from collision cascade sputtering; solid lines: contribution from electronic sputtering based upon laboratory measurements.

**Fig. 6.**—Low-energy ion spectra from the low-energy charged particle (LECP) experiment on Voyager 1 at several different distances in the vicinity of Io. The dashed line corresponds to measured data and the best estimate extrapolation of the data to lower energies. The energy scale is expressed in terms of the energies corresponding to three possible different ions detected in the LECP instrument (see text).
ments to higher energies. The LECP spectra are shown under the assumptions of pure hydrogen, oxygen, and sulfur ions. This two-humped type spectra in the innermost magnetosphere, close to Io, has been commented upon previously by Belcher, Goertz, and Bridge (1980).

The ion energy spectrum in Figure 7 is used together with the erosion yields as a function of energy (Fig. 5) and the determined temperature dependence of the fast-ion erosion (Fig. 4) to obtain the SO$_2$ erosion yield as a function of temperature. The results are shown in Figure 8 and are compared to the sublimation curve for sulfur dioxide. (100% coverage of Io by SO$_2$ is assumed for simplicity). The upper (A) axis in the figure gives the equivalent Io zenith angle of the Sun ($0^\circ = $ equator) based on the estimates of Fanale et al. (1981b), in which the variations of the albedo are used to estimate average vapor pressures. The lower (B) axis gives the equivalent zenith angle ($180^\circ = $ equator on the night side) from the observed albedo (Fanale, Banerdt, and Cruikshank, 1981).

The solid lines for the ions on Figure 8 are for erosion only by the fast ions. As noted above, the temperature dependence of the erosion yields has been used, giving an increased erosion with increasing temperature. The temperature dependence observed in Figure 4 is extended to other incident ions and energies using the model of Brown et al. (1980b). Erosion by the reported plasma ions alone is given by the dashed line. A fast-ion particle population composed primarily of sulfur (a not unreasonable scenario) is only a factor of 3 less efficient than the much more plentiful slow plasma ions in producing SO$_2$ erosion in the absence of an atmosphere. Erosion by the sulfur and oxygen fast ions dominates sublimation below $\sim$ 90 K. Even a pure hydrogen and helium fast ion flux would dominate sublimation for temperatures below approximately 80 K.

Matson and Nash (1981) suggest, however, that the surface temperature of Io does not determine the interchange of molecules between the surface and atmosphere in the manner suggested by the sublimation curve.
Results predicted by their subsurface cold trapping model are one to two orders of magnitude lower than temperatures determined from the measured albedo because of the assumed porous surface. The high porosity causes atmospheric gases to become stored in cold traps. A high porosity may also modify the particle erosion process considerably. The erosion yields could be expected to increase because of the irregular nature of the surface, which would increase the likelihood of grazing incidence, while escape from the surface would be controlled by the probability of re-adsorption, which is high. Although not yet experimentally determined for SO$_2$ films, thin layers (few monolayers to a few hundred Å) might tend to increase the yield per ion for SO$_2$ condensed on an insulating surface (Ollerhead et al. 1980). However, for very thin layers, the erosion will obviously be limited by the number of condensed surface molecules available. In summary, if the subsurface cold trapping model for Io's surface is correct, fast-ion sputtering might dominate sublimation in those regions of Io's surface on which SO$_2$ gases are trapped.

The penetration depth through an SO$_2$ atmosphere as a function of energy for hydrogen, oxygen, and sulfur incident normally on the surface is shown in Figure 9 employing the same stopping data used in Figure 3. The lower limit on the particle penetration in an atmospheric gas goes roughly as $3/2 \sigma$, where for a triatomic molecule $\sigma \sim 3\sigma_d$ and $\sigma_d \sim 1.8\text{Å}^2$ (Sigmund 1969) is an atomic cross section parameter for fast particles. For an atmosphere with column density $\gtrsim 10^{18}$ parts cm$^{-2}$, only the fast incident ions in the Jovian plasma penetrate to the surface producing erosion, an example of a self-limiting atmosphere under particle bombardment of the surface as pointed out by Lanzerotti et al. (1978a).

An intrinsic magnetic field (e.g., Neubauer 1978; Kivelson, Slavin, and Southwood 1979) would also shield most of the surface, primarily from the lower energy particles. Estimations of the cutoff energy depend greatly on the size of the ambient field and the orientation of the dipole axis with respect to the local planetary field. Preferential regions on the satellite could be impacted by the charged particles if there is an intrinsic magnetic field (see, for example, Hill, Dessler, and Fanale 1979; Ip 1981). In the magnetic polar regions of the satellite, all particles could conceivably be incident on the surface, whereas lower energy ones would be completely excluded in the equatorial regions.

Nelson et al. (1980) note that the Io longitudes $72^\circ < \theta < 137^\circ$ have the greatest abundance of sulfur dioxide frost, whereas longitudes between $250^\circ < \theta < 323^\circ$ are least abundant. These data could be consistent with preferential sputtering in the latter longitude band by Jovian particles if the satellite has a magnetic field. Particle ray tracing to determine the consistency of this suggestion is required. Alternatively, a diminished atmosphere on the night side and at the poles would allow rapid sputter removal of SO$_2$ by fast ions from these regions (Matson and Nash 1981). We note, however, that such a longitude dependence could also be highly temporal because of variability in volcanic activity, as well as in the location of active volcanos as a function of time. An additional preferential bombardment certainly occurs if flux tube ions impinge on the surface.

Plotted in Figure 10 are the erosion rates of SO$_2$ by H$^+$, O$^+$, and S$^+$ fast ions and by the plasma ions, as functions of atmospheric column density. The plasma penetration is limited by a column density of $\sim 6 \times 10^{15}$ molecules cm$^{-2}$ as seen in Figure 9. The fast-ion penetration also becomes limited, as indicated by the dropoff in the H$^+$ and O$^+$ erosion yields at the highest column densities. The slow decrease of the flux below the peak produced by the fast ions reflects the temperature dependence of the yield from Figure 8, using the temperature scale on the right-hand side of Figure 10. The right-hand side indicates the corresponding surfacertemperature if the atmospheric column density on the left-hand scale is produced by sublimation from a nonporous surface. (The effective atmospheric temperature might, however, be different than that of the surface because of direct heating by the flux of ions; Watson 1982.) Again, these considerations assume, for simplicity, 100% coverage of Io by SO$_2$. In the absence of such
coverage, a patchy atmosphere would be excited, resulting in considerable transport of SO₂ across the surface.

The dashed lines in Figure 10 are the expected atmospheric loss rates due to electron ionization and charge transfer by incident corotating plasma. Here we assume an electron plasma of 2000 electrons cm⁻³ with a temperature in the vicinity of Io of ~5–10 eV (Scudder, Sittler, and Bridge 1981), or a flux of ~3×10¹⁵ cm⁻² s⁻¹. This implies a frequency (Kumar 1979) of the order of 1–2×10⁻⁴ s⁻¹. The order of one-third of the electrons may be energetic enough to ionize an SO₂ molecule before the electrons lose their energy to vibrational excitation. Further, charge exchange cross sections for H⁺ and O⁺ on SO₂ are ~10 A², but for S⁺ are ~10 A² at the corotation velocity. We use here 10 A² and the corotation velocity to describe this process.

Each ionization in an exosphere can be assumed to result in the “loss” of an SO₂ molecule because of sweeping of the ion by the corotating magnetic field either into the surface or out of Io’s gravitational field. For a very low density atmosphere, reimpacting ions can produce additional collision cascade sputtering (Matson, Johnson, and Fanale 1974). Haff, Watson, and Yung (1981) point out that for high ionization probability, such a process can enhance the yields on the trailing side.

If ionization in an exosphere were the dominant loss mechanism, then a column density, ~2.5×10¹⁵ particles cm⁻² could result on the trailing side, as indicated by the crossing of the plasma production line and the electron ionization loss line. The effect of the fast ions depends on the mix of H⁺, O⁺, and S⁺. If the electron flux is suppressed close to Io by a weak field, the estimates of column density will depend on charge exchange loss. For example, if one-sixth of the fast ions are S⁺ and loss occurs only by charge exchange, a column density of the order 10¹⁶ molecules cm⁻² could be produced in the absence of other loss mechanisms. Such an atmosphere could easily support an ionosphere, as suggested by Cloutier et al. (1978), the ionosphere being produced by the incident fast ions and electrons.

The lower estimate of the atmosphere on the trailing side (~2.5×10¹⁵ particles cm⁻²) is still very important as it would limit the gravitational escape of sputtered species from the surface and hence restrict the supply of atoms and molecules to the Io corotating neutral clouds. Note that an ionization rate (normalized to Io’s radius) of ~10¹⁰ ions cm⁻² s⁻¹ is the order of magnitude required to supply the plasma torus (Shemansky, 1980). Again, these estimates are based on 100% coverage of Io by SO₂ frosts. Such estimates assume a cold surface and/or a porous surface (Matson and Nash 1981) for which sublimation is suppressed. At ~95 K the electron ionization loss is equal to the SO₂ sublimation rate.

A competing loss process would be the sticking to the surface of reimpinging neutrals. If the sputtered molecules are all nondissociated SO₂, this would clearly be the dominant loss mechanism. A column density based on this limiting process can be estimated from (Johnson et al. 1981)

\[ N \approx \frac{1}{k} i \Phi_{\text{NET}}, \]

where \( i \) is the mean time for the ballistic trajectory of the sputtered or sublimated neutrals, \( k \) is a sticking coefficient, and \( \Phi_{\text{NET}} \) is the production flux (Fig. 10) less the direct escape flux. The mean time depends on the escape velocity, the satellite radius, and the nature of the velocity spectra of the neutrals. If the sticking coefficient is also of the order of unity (as it may well be for SO₂ molecules), then column densities \( \lesssim 10^{14} \) molecules cm⁻² produced by sputtering would be expected.

Watson (1981) has considered such atmospheres in more detail. On the other hand, if the sputtered molecules contain a significant O₂ component, as is the case for sputtered H₂O (for \( T \geq 140 \) K; Brown et al. 1981; V. Pirronello, G. Strazzulla, and G. Foti, in preparation, 1981), the situation might be different since the O₂ would not “stick” readily (i.e., would not reside on the surface for long times unless the surface is highly porous or the temperature is very low).

We note that the largest SO₂ or O₂ column densities suggested by Figure 10 are of the order or larger than the ~10¹⁷ molecules cm⁻² upper limit determined by
Butterworth et al. (1980) from Earth-orbit using the International Ultraviolet Explorer satellite. This upper limit is considerably less than that deduced from the Voyager infrared instrument (IRIS) and has been attributed by Butterworth et al. (1980) to the possible existence of transient production conditions on Io or, more likely, to patchy atmospheric conditions that may arise because of the existence of patches of solid deposits (perhaps as evidenced in the Voyager pictures) and volcanic venting. It may also be possible that a significant atmosphere produced by sputtering could exist on the night side of the satellite; such an occurrence would give rise to the interesting possibility of SO\textsubscript{2} winds (in the hydrodynamic limit) on the satellite.

V. SUMMARY

Sputtering yields for SO\textsubscript{2} by incident ions have been measured and estimated based on existing models. The sputtering yields by the fast ions are observed to be large and hence complete with the predominant slow ions in producing erosion of the SO\textsubscript{2} deposited by volcanic activity on Io. These components differ in two respects: penetration of the atmosphere and directions of impact. The largest sputtered fluxes produced here are of the same order of magnitude as the required source strength of atoms (S and O) to supply the observed neutral cloud in the vicinity of Io (Kumar 1979). There may be a problem in removing the molecules from Io’s gravitational field, except, possibly, by ionization and/or sweeping by the magnetosphere. As the surface is certainly not pure SO\textsubscript{2} (unless this gas is trapped ubiquitously in a porous surface), sputtering from the surface of this gas alone might not be the sole supply of the neutral cloud. This could be changed if the incident flux of flux tube ions, not included in the present estimate, play a major role or if reimpact sputtering is important. The sputtering process can, however, create a tenuous atmosphere and will compete with deposition by volcanism or condensation from an atmosphere by removing molecules or transporting them large distances.

The work at the University of Virginia was supported in part by NSF grant AST-79-12690-1 and NASA grant NAGW-186. The work at the University of Kansas was supplied in part by subcontract from Johns Hopkins University Applied Physics Laboratory, where the Voyager LEC program is supported by NASA under Task I of contract N00024-78-C-5384 between JHU and the Department of the Navy. We thank S. M. Krimigis, C. Musil, A. Cheng, and V. Pirronello for technical assistance and helpful comments and D. L. Matson for a careful reading of the manuscript.

REFERENCES


T. P. ARMSTRONG: Department of Physics, University of Kansas, Lawrence, KS 66044

W. M. AUGUSTYNIK, W. L. BROWN, and L. J. LANZEROTTI: Bell Laboratories, 600 Mountain Avenue, Murray Hill, NJ 07974

R. E. JOHNSON: Department of Nuclear Engineering and Engineering Physics, University of Virginia, Charlottesville, VA 22901