PLASMA ION-INDUCED MOLECULAR EJECTION ON THE GALILEAN SATellites: ENERGIES OF EJECTED MOLECULES

R. E. Johnson, J. W. Boring, C. T. Reimann,
L. A. Barton, E. M. Sievaka, J. W. Garrett,
K. R. Farmer

Department of Nuclear Engineering and Engineering Physics
University of Virginia, Charlottesville, Virginia 22901

W. L. Brown and L. J. Lancerotti
Bell Laboratories
Murray Hill, New Jersey 07974

Abstract. First measurements of the energy of ejection of molecules from icy surfaces by fast incident ions are presented. Such results are needed in discussions of the Jovian and Saturnian plasma interactions with the icy satellites. In this letter parameters describing the ion-induced ejection and redistribution of molecules on the Galilean satellites are recalculated in light of the new laboratory data.

Introduction

The surfaces of the Galilean satellites of Jupiter are thought to be bombarded by ions of the Jovian magnetospheric plasma (Matson et al., 1974; Lancerotti et al., 1978; Pilcher, 1978). Such bombardment would efficiently sputter the ice which has been observed to be on the surfaces of Europa, Ganymede, and Callisto (Pilcher et al., 1972; Lebofsky, 1977). Laboratory measurements of the charged-particle erosion of these surface materials have been combined with satellite-measured incident particle fluxes to compare the rates of the sputter ejection of molecules with the rates of ordinary sublimation. The results have then been used to estimate the net loss of surface material to space, 'atmospheric' column densities for the ejected molecules, the erosion of surface features, and the net redistribution of volatile material across the satellite surfaces (Lancerotti et al., 1978; Haff et al., 1979, 1981; Johnson et al., 1981, 1982; Watson, 1981; Brown et al., 1982b; Sievaka and Johnson, 1982). These past estimates required assumptions about the energy and mass distributions of the ejected molecular species.

In this letter we report representative measured energy spectra of ejected molecules for the ion erosion of water ice. These measurements, which are found to be different that the model energy spectra used in the earlier works, are used to re-evaluate those parameters needed to estimate surface loss, 'atmospheric' column densities and surface redistribution produced by charged particle impact on the icy satellites. The experimental details and the underlying physics of the ejection process are reported elsewhere (Boring et al., 1983).

Ejected Molecule Energies and Masses

In an earlier paper on ion bombardment of D2O ice, (Brown et al., 1982a), we reported that, in addition to D2O molecules, D2 and OD2 molecules were ejected in significant quantities, depending upon the temperature of the ice. The measured sputtering yields as a function of temperature for D2 and D2O behaved very differently from that of D2O, the former two having a strong temperature dependence over a broad range of surface temperatures (20-150 K). In contrast, the erosion rate of D2O was constant up to a temperature of ~120 K.

Using time-of-flight techniques we have obtained energy spectra for the molecules ejected from a D2O target by incident ions. Figure 1 contains such spectra for ejected D2O molecules for three different ion-type, ion-energy combinations. These results span the velocity range in which the energy deposited in the material is predominantly in the form of electronic excitation and ionization (higher ion velocities) to the case in which most of the energy is deposited in direct collisions with the atoms in the material (lower ion velocities). The yields in Fig. 1 are not absolute. Rather, in order to compare the fraction of particles emitted in a given energy interval, they have been normalized at an ejection energy of 1 eV. The spectra in Fig. 1 are seen in all cases to have the same energy dependence at the larger energies. As the fraction of the electronic energy deposited increases (50 keV Ar+ to 1.5 MeV Ar+ to 1.5 MeV He+) a larger fraction of lower energy particles are ejected, as expected.

The ejection of molecules by fast ions, such as the He+ in Figure 1, were assumed in our earlier works to have a Maxwell-Boltzmann
energy dependence. Such distributions have a distinct maximum and decay more rapidly with increasing energy than do the distributions in Figure 1. For lower energy particles, an energy distribution characteristic of collisional sputtering in metals was used (\(Y(E) \sim E/(U+E)^2\) where \(U\) is the surface binding energy). The 50 keV data in Figure 1 fits such a form, but with a value for \(U\) a factor of 10 smaller than the surface binding energy of D,O ice.

Figure 2 presents, for one ion-energy combination, the energy spectra for ejected D_2O and O_2. At \(\sim 80\) K the O_2 yield is much smaller than that of D_2O. Otherwise the energy spectra are quite similar, which was found to be the case for other ion-energy combinations. The energy spectra observed for D_2O and O_2 are very nearly temperature independent over the temperature region for which we have measurements, (from 12K to 120K for ejected D_2O and 12K to 80K for ejected O_2) whereas the energy spectra for the D_2 are not. Further, the spectra appear to be relatively insensitive to the incident particle energy and type except insofar as there are changes in the relative amounts of collisional and electronic energy loss.

**Satellite Calculations**

We have used representative energy spectra to calculate the sputter-induced escape fractions and mean velocities of the escaping molecules O_2 and H_2O for Europa, Ganymede, and Callisto (Table 1). The energy spectra used were assumed the same for H_2O and O_2 molecules sputtered from H_2O ice as for D_2O and O_2 sputtered from D_2O ice. The calculations were performed using escape energies (Table 1) which correspond to that energy required for a molecule to reach a distance away from the satellite surface equal to the average of the two colinear Lagrange points. At such distances the force of the satellite on the molecule is approximately equal to the force of the planet on the molecule. Because the energy spectra in Figs. 1 and 2 decrease slowly with energy relative to a thermal velocity distribution, the escape fractions are not nearly as sensitive to the satellite escape energies as indicated in the earlier estimates of Johnson et al. (1982). The velocities given in Table 1 are the average value of the velocities of the escaping molecules reduced by the escape velocity. In the absence of ionization by plasma electrons, these velocities are large enough that the escaping molecules would distribute over distances large compared to the distance between a satellite and Jupiter.

Also shown in Table 1 are the mean energies of those molecules which remain gravitationally bound to the satellite, the mean times for these molecules to return to the surface, and the mean excursion distances across the surface. These quantities are calculated assuming the molecules travel in collisionless, ballistic trajectories across a satellite. The time for return to the surface by an ejected molecule with an energy less than the escape energy is \(t = 2r^3/\mu D/R\), integrated from the surface to maximum excursion distance. The mean flight times and excursion distances are calculated by averaging \(t\) and the cosine of the angular displacement over the measured energy and angular distributions for molecules with energies less than the escape energy. The angular distributions of the ejected molecules have been found to be close to a cosine distribution.

Johnson et al. (1981, 1982) calculated the flux of particles sputtered from the surface of each of the ice covered satellites (assumed 50% ice covered) of Jupiter based on Voyager 1 LECP data (Krueger et al., 1981; Hamilton et al., 1981). The LECP fluxes were assumed to be either all protons or all oxygen ions, in order to obtain upper and lower bounds on the sputtered fluxes at the surface. Further, the increase in yield which would occur at temperatures typical of the sub-solar regions (Johnson et al., 1982) was ignored. Recent studies indicate that the surfaces of these satellites may be nearly completely ice covered, with observed darkening perhaps produced by small amounts of contaminants (Clark, 1980). We use the sputtering flux given by Johnson et al. (1981), which assumes 50% ice coverage and a smooth surface. We assume 80% of the erosion produced is associated with ejection of H_2O and 20% with O_2, based on recent measurements at 100 K. This is a somewhat smaller fraction of O_2 than reported earlier (Brown et al., 1982a). With the above assumptions about the surfaces and the sputtered flux, and with the escape fractions given in Table 1, we can make direct escape flux from each satellite surface and the net loss of surface material can be calculated. If the LECP ions incident on the satellite surfaces are mostly oxygen or sulfur, the plasma ion velocities span the velocity range covered by the 50 keV and 1.5 MeV Ar^+ ions. We therefore use a simple average of these two sets of experimental results to describe heavy ion bombardment. In the following we use oxygen ions as representative of the heavy ion component (Johnson et al., 1981).

The results of Table II confirm that, because the escape fractions are small for these satellites, the net erosion by the incident magnetosphere particle fluxes measured by the LECP instrument is small geologically unless this flux contains a significant fraction of heavy ions such as oxygen. A significant energetic oxygen (sulfur) population in the plasma is likely to exist in the vicinity of Europa. The total loss of material will be increased by ionization and subsequent plasma sweeping of the molecules in bound ballistic orbits. As the molecule flight times in Table I are much smaller than the ionization lifetimes of the molecules, this effect is small.

The numbers in Table II can be used together with the data of Sieveka and Johnson (1982) to give the net transport of material to the poles because of the pitch angle anisotropy of the LECP fluxes. They calculated profiles for the ion sputter-induced redistribution of material across the satellite surfaces. Their redistribution profiles were parameterized by the ratio of the energy peak in the assumed sputtered spectrum to the gravitational escape energy. As the measured spectra have ill-defined "peaks", we can use the mean energy of bound particles to relate the measured distributions to the profiles calculated by Sieveka and Johnson (1982). Using the H^+ spectra to describe fast, light ions bombarding Ganymede, the appropriate redistribution profile is similar to the one labeled 0.098 in Figure 5 of Sieveka and Johnson (1982). From such a profile a net deposition of material occurs above about 30° latitude, close to the lower edge of Ganymede's polar frost cap (Smith et al., 1979). Further, the net deposition in the polar region in 10^5 years would be \(-2\text{ to } -5\) cm if the LECP flux is all protons and \(-5\text{ to } -10\) m if it is all oxygen ions. On Europa these redistribution profiles are important.
TABLE I. Sputtering of \( \text{H}_2\text{O} \) Ice on Galilean Satellites

<table>
<thead>
<tr>
<th></th>
<th>( \text{He}^+ ) (1.5 MeV, 68°K)</th>
<th>( \text{Ar}^+ ) (1.5 MeV, 80°K)</th>
<th>( \text{Ar}^+ ) (50 keV, 25°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{H}_2\text{O} )</td>
<td>( \text{O}_2^* )</td>
<td>( \text{H}_2\text{O} )</td>
</tr>
<tr>
<td>Escape Fractions†</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>.07</td>
<td>.04</td>
<td>.14</td>
</tr>
<tr>
<td>Ganymede</td>
<td>.04</td>
<td>.03</td>
<td>.08</td>
</tr>
<tr>
<td>Callisto</td>
<td>.05</td>
<td>.03</td>
<td>.10</td>
</tr>
<tr>
<td>Mean Velocity of Escaping Molecules (km/sec)‡</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>3.7</td>
<td>3.5</td>
<td>3.9</td>
</tr>
<tr>
<td>Ganymede</td>
<td>4.7</td>
<td>3.8</td>
<td>4.1</td>
</tr>
<tr>
<td>Callisto</td>
<td>4.3</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Mean Energies of Gravitationally Bound Molecules (eV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>.07</td>
<td>.08</td>
<td>.08</td>
</tr>
<tr>
<td>Ganymede</td>
<td>.08</td>
<td>.09</td>
<td>.11</td>
</tr>
<tr>
<td>Callisto</td>
<td>.07</td>
<td>.08</td>
<td>.10</td>
</tr>
<tr>
<td>Mean Flight Time for Gravitationally Bound Molecules (10^3 sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>1.8</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1.5</td>
<td>1.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Callisto</td>
<td>2.5</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Mean Excursion Distance Across Surface (in satellite radii)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>.59</td>
<td>.41</td>
<td>.70</td>
</tr>
<tr>
<td>Ganymede</td>
<td>.41</td>
<td>.29</td>
<td>.54</td>
</tr>
<tr>
<td>Callisto</td>
<td>.51</td>
<td>.35</td>
<td>.63</td>
</tr>
</tbody>
</table>

* Used the mass 20 energy spectra for both the mass 18 and the mass 32 spectra for 1.5 MeV \( \text{He}^+ \).
† Obtained using escape energies in Table II.

when describing the competition between sulfur implantation and surface erosion. Using the \( \text{Ar}^+ \) 50 keV energy spectrum as characteristic of the low energy ion bombardment, the loss of surface produced by co-rotating ions at the equator would be about half that estimated earlier using the same assumed yields and plasma composition.

In the absence of significant sublimation (e.g., \( T \leq 110° \)K) the gravitationally bound molecules form a collisionless atmospheric corona. The column densities of such 'atmospheres' are calculated using the sputtered surface fluxes, the escape fractions, and the mean flight times in Table I. The column densities given in Table II are smaller than those estimated by Johnson et al. (1981) (Eq. (2) of that paper gives results too large by a factor of 2). The estimates given here are seen to be well below the atmospheric limits found for these satellites and are smaller than an exospheric column density. The calculated column densities are lower limits. That is, we ignore the temperature dependence of the sputtering yield and sublimation (particularly in the subsolar regions). Further, those molecules which escape have not been included (Watson, 1981). More importantly, unit sticking probability has been assumed. This is an appropriate assumption for the \( \text{H}_2\text{O} \) molecules at the temperatures of interest, but not for the \( \text{O}_2 \) molecules ejected, particularly in the

TABLE II. Bombardment by LEPV Voyager I Particles † ‡

<table>
<thead>
<tr>
<th></th>
<th>Escape Flux† (H( \text{O}_2 ) cm/sec)</th>
<th>Surface Loss (( \text{cm}^2/\text{yr} ))</th>
<th>Column Density† (( \text{cm}^2/\text{yr} ))</th>
<th>Escape Energies** (eV/amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Protons Incident</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>( 5 \times 10^6 )</td>
<td>5</td>
<td>( 1 \times 10^{13} )</td>
<td>0.020</td>
</tr>
<tr>
<td>Ganymede</td>
<td>( 2 \times 10^6 )</td>
<td>2</td>
<td>( 8 \times 10^{10} )</td>
<td>0.037</td>
</tr>
<tr>
<td>Callisto</td>
<td>( 2 \times 10^5 )</td>
<td>0.2</td>
<td>( 1 \times 10^{10} )</td>
<td>0.028</td>
</tr>
<tr>
<td>All Oxygen Ions Incident *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>( 2 \times 10^6 )</td>
<td>( 2 \times 10^3 )</td>
<td>( 2 \times 10^{13} )</td>
<td>0.020</td>
</tr>
<tr>
<td>Ganymede</td>
<td>( 6 \times 10^5 )</td>
<td>( 6 \times 10^2 )</td>
<td>( 1 \times 10^{13} )</td>
<td>0.037</td>
</tr>
<tr>
<td>Callisto</td>
<td>( 7 \times 10^4 )</td>
<td>( 7 \times 10^1 )</td>
<td>( 2 \times 10^{12} )</td>
<td>0.028</td>
</tr>
</tbody>
</table>

† Obtained using escape energies in Table II.
‡ Based on an average of the data in Table I for \( \text{Ar}^+ \) at 50 keV and 1.5 MeV.
** Energies required to reach the mean of the co-linear Lagrange points.
† Net loss of \( \text{H}_2\text{O} \) either as \( \text{H}_2\text{O} \) or \( \text{H}_2 \) and \( \text{O}_2 \) molecules.
‡ Net column density of O atoms either as \( \text{H}_2\text{O} \) or \( \text{O}_2 \) molecules.
++ Absolute yields from Johnson et al., 1981.
sub-solar regions (Brown et al., 1982; Johnson et al., 1982). Whereas the results in Table II may change as more is learned about the plasma and the satellite surface compositions, the results in Table I can be used by the planetary science community as a tool for understanding plasma-satellite interactions.

Acknowledgements. Work at the University of Virginia is supported by the NSF Astronomy Division under Contract AST-82-00477 and the NASA Earth and Planetary Exploration Division under Contract NAGW-186.

REFERENCES


(Received February 9, 1983; accepted March 22, 1983.)