SPUTTERING OF ICE BY LOW ENERGY IONS: EFFECTS ON ICE GRAINS AND ICY SATELLITES IN SATURN'S INNER MAGNETOSPHERE. M. Famá[1], R. E. Johnson[1,2], J. Shi[1], R. A. Baragiola[1], M. Liu[1], E. C. Sittler Jr.[3], H. T. Smith[4], [1]University of Virginia, Charlottesville, VA 22904, [2]New York University, New York, NY 10003, [3]Goddard Space Flight Center, Greenbelt, MD 20771, [4]Johns Hopkins University, Laurel, MD 20723

Introduction: Icy grains and satellites orbiting in Saturn's magnetosphere are immersed in a plasma that sputters their surfaces. This limits the lifetime of the E-ring grains and ejects neutrals that orbit Saturn until they are ionized and populate its magnetosphere. Modeling the production of tenuous atmospheres or estimating the lifetime of icy grains requires reliable values for the plasma parameters and also accurate laboratory data for the sputtering yields at ion energies and ice temperatures relevant to those environments. Here we re-evaluate the sputtering rate of ice in Saturn's inner magnetosphere using the recent Cassini data on the plasma ion density, temperature and composition [1] and a recent measurements and analysis of relevant sputtering data for ice [2].

Sputtering of Ice: For atomic targets, the standard linear collision cascade theory (SCL) predicts that the elastic sputtering yield is proportional to the nuclear-stopping cross section S_n. The proportionality factor is inversely proportional to the elastic differential cross section in the binary collision approximation, and it is also inversely proportional to the surface-binding energy of the target atoms. Molecular targets, on the other hand, contain internal chemical structure which can absorb some of the elastic energy transferred to the molecule into internal inelastic energy, rather than being used for displacement of molecules. For this reason we tested the validity of the SCL theory for water ice in an extended range of energies using a modified elastic scattering differential cross section. Additionally, we include electronic sputtering that occurs due to long lived repulsive electronic excitations which lead to atomic or molecular motion. The extant literature is consistent with the total electronic sputtering yield Y being proportional to S_e^2, where S_e is the electronic stopping cross section. Including a term proportional to S_n and another term proportional to S_e^2, we could fit a complete analytical expression for the total sputtering yield of water ice valid for temperatures and projectile energies relevant to the astrophysical environments of interest. Figure 1 shows a comparison of our model with the available experimental data for the sputtering yield of ice.

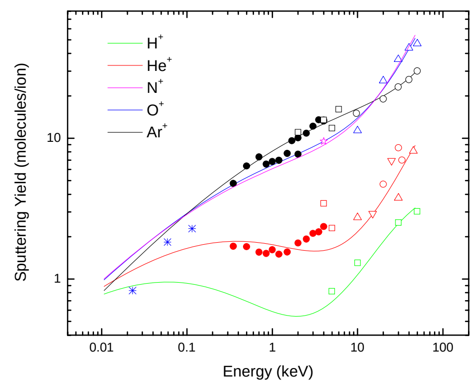

Figure 1 *Solid and open symbols: experimental data for the sputtering yield of ice for H, He, N, O and Ar ions from Ref. [2] and references therein. The solid lines represent our model for Y. Crosses: Molecular dynamics simulations.*

Saturnian Plasma: Since heavy ions with energies > 10 keV were found to be the dominant sputtering agent for icy materials in the Jovian magnetosphere [3], this was initially assumed to be the case also at Saturn [4,5]. Cassini data showed that the presence of a relatively dense and extended population of neutrals suppresses the very energetic ions in the region inside of 10 R_S. The energetic electron population, which at Europa contributes to forming the O_2 atmosphere, is also considerably reduced in Saturn's inner magnetosphere (<~ 15 R_S; [6]). Therefore, the erosion of E-ring grains and sputtering of satellite surfaces inside the orbit of Rhea is likely dominated by ions with energies <10 keV, opposite to what was assumed in earlier research. Figs. 2a and 2b give the ion densities and temperatures in Saturn's inner magnetosphere as measured by the CAPS instrument [1]. These are given in Saturn's equatorial plane as a function of radial distance from Saturn from 3.5 to 10 R_S ($R_S \approx$ 60,268 km), a region orbited by many of the icy satellites and the E-ring grains. The plasma is primarily produced from the water plumes on Enceladus and the densities are given for H^+ and for water-like species summed together as W^+ (O^+, OH^+, H_2O^+, and H_3O^+). The composition of this component varies with radial distance, with H_3O^+ being an important contribution near Enceladus (~4 R_S) and O^+ becoming dominant by

10 R_S near the orbit of Rhea [1]. Although Fig. 2 gives a single temperature at each value of R, the plasma ion velocity distributions are not isotropic. The velocity distribution is divided into components perpendicular to the local magnetic field, $T_\perp$, and parallel, $T_{//}$, with T = $(2T_\perp + T_{//})/3$. The relative contribution of these to the total flux differs between ions and varies slowly with R. Sittler et al. [1] suggests $T_{//}/T_\perp \sim 0.5$ for protons and $T_{//} / T_\perp \sim 0.2$ for W^+ at the magnetic equator. Such ratios indicate that the ion lifetimes are too short for the temperature to isotrophize.

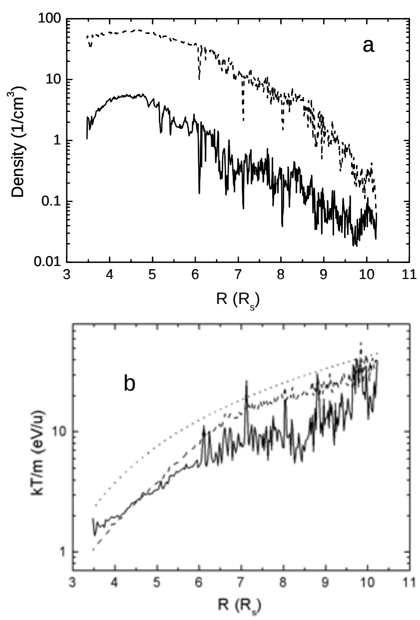

***Figure 2** (a) shows the ion densities in Saturn's inner magnetosphere as measured by the CAPS instrument. The densities are given for H^+ (solid line) and water-like species summed together as W^+ (O^+, OH^+, H_2O^+, and H_3O^+) (dashed line); (b) shows the ion temperatures for H^+ (solid) and W^+ (dashed) measured relative to the plasma flow speed. The dotted line in (b) corresponds to the energy associated with the flow past a grain or satellite orbiting in Saturn's magnetosphere.*

Since these temperatures are measured relative to the plasma flow speed, we also show in Fig. 2b the energy associated with the flow past a grain or satellite orbiting in Saturn's magnetosphere. That is, the ions obtain gyro-motion on pick-up given as $m_i\,(\boldsymbol{v_{co}}-\boldsymbol{v_o})^2/2$, where $\boldsymbol{v_{co}}$ is the tangential velocity of rotation of the magnetic field which confines the plasma, and $\boldsymbol{v_o}$ is the orbital speed of the body. Since Saturn's field is closely aligned with its spin axis, for bodies in circular orbit these velocities have, roughly, the same direction; Using Saturn's rotational speed and gravity at its equator, the speeds are $v_{co} \approx 9.87\mathrm{R(R_S)}$ km/s and $v_o \approx 25.1 / [\mathrm{R(R_S)}]^{1/2}$ km/s, where R is the radial distance in R_S. These ion speeds and densities are used to calculate sputtering rates.

Sputtering Flux: Using the ion density, n_i, and velocity distribution, $f(\boldsymbol{v})$, along with the sputtering yield above, the surface-averaged ion flux impacting the surface and the surface-averaged sputter flux can be written:

$$\Phi_i = \iint [-\mathbf{n}\cdot(\mathbf{u}+\mathbf{v})] n_i\, f(\mathbf{v}) d^3 v \frac{d\Omega_s}{4\pi}$$

$$\Phi_{sputtering} = \iint Y(E_i)[-\mathbf{n}\cdot(\mathbf{u}+\mathbf{v})] n_i\, f(\mathbf{v}) d^3 v \frac{d\Omega_s}{4\pi}$$

Here **u** is the average flow velocity of the ions relative to the body and **n** is the local surface normal. The flux is averaged over the body by integrating $d\Omega_s$ over the direction of the surface normal which varies with the position on the body.

The net sputter flux of icy surfaces in the Saturnian system is seen to be primarily due to the water ion group and is non-negligible even though the energetic ion component of the plasma in Saturn's inner magnetosphere differs from that in the Jovian magnetosphere, both in the absence of a significant 'hot' component (>10 keV) and in the absence of energetic sulfur ions which sputter very efficiently [3]. It is also seen that for the sputtering of the icy satellites in the Saturnian system, where the $(v_{co}-v_o)$ is much smaller than it is for the icy jovian satellites, the yield is sensitive, not surprisingly, to the ion temperature. Therefore, accurate ion temperatures, as well as ion composition are important in determining satellite and grain erosion rates. Here we have used recently available data, as described above, so that the lifetime of the E-ring grains and the sputter contribution to the neutral torus can now be estimated.

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