NOTE

Application of Laboratory Data to the Sputtering of a Planetary Regolith

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Expressions for laboratory sputtering data are examined in order to describe the effective yield from a planetary regolith composed of, roughly, spherical grains. It is shown that for a fully exposed regolith the effective yield is of the order of 0.4–1 times the measured yield at normal incidence on a laboratory surface depending on the nature of the sputtering process. © 1989 Academic Press, Inc.

Plasma ion erosion of the surfaces of satellites and grains imbedded in the solar wind or a planetary magnetosphere has been a topic of considerable interest (e.g., Cheng et al. 1986, Johnson et al. 1984). The incident plasma particles modify surfaces at the microscopic level (Taylor 1982, Johnson et al. 1983, Auciello and Kelly 1984, Calcagno et al. 1985) changing the reflectance properties of the surface (e.g., Brown et al. 1978, O'Shaughnessy et al. 1988, Strazzulla et al. 1988). When the local erosion rate of the surface is of interest, Hapke (1986) has pointed out that care must be taken in applying laboratory data on sputter erosion to plasma erosion of a planetary regolith. This is because surface roughness and redeposition of sputtered products on adjacent grains can control the net ejected molecule flux. Hapke and Cassidy (1978) and Carey and McDonell (1976) evaluated this effect for a lunar surface. In the outer Solar System, however, more volatile species are condensed and the sputtering mechanisms change (Brown et al. 1982). A simple correction for rough icy surfaces was suggested by Sieveka and Johnson (1982) and has been used in most evaluations of satellite surface erosion (e.g., Johnson et al. 1984, Cheng et al. 1986, Johnson et al. 1988). In this paper laboratory sputtering yields are used to evaluate plasma erosion yields for a regolith. This study takes into account roughness and sticking to neighboring grains for a fully exposed regolith; i.e., ignore crater shadowing. The suggestion of Hapke (1986) is followed below and an alternate procedure is given in the Appendix.

Expressions for the effective yield from a planetary regolith are obtained using laboratory data to calculate a sputtering function for an individual grain, $y$. If the yield from an isolated grain can be written in the form

$$y(g) = \frac{Y}{4\pi}(1 + b \cos g), \quad 1 > b > -1, \quad (1)$$

where $Y$ is the total yield from the grain, and $g$ is the angle between the incident ion direction and the ejected species direction (Figs. 1a and 1b), then the results of Hapke (1981) for scattering of light from grains can be used to give the sputtering by incident ions from a regolith (Hapke 1986). In this description the “scattered” species are the sputtered neutrals, $Y$, replaces the so-called single-scattering albedo, $w$, and $(4\pi)^{-1}(1 + \cos g)$ is the phase function (Appendix). This analogy simply acknowledges that the transport equations are similar for sputtering and light scattering. As the effect of the regolith has been worked out by Hapke (1981) for the form in Eq. (1) it is reasonable to use this to consider the sputtering problem. However, for sputtering of a regolith only single scattering will be allowed (i.e., sputtered particles striking another grain stick with near unit efficiency).

For “single scattering” the total yield from a regolith composed of spherical grains with $Y$ given above is obtained from the transport equations (Hapke 1981).

$$\bar{Y}(i) = \frac{Y_0}{2} \left[ 1 + \frac{b}{2} \cos(i) \right], \quad (2a)$$

as pointed out by Hapke (1986). Here $(i)$ is the “illumination” angle for the planetary surface (angle between the incident particle and the normal to the average surface, Fig. 1c) and $Y(i)$ is called the “single-scattering” limit of the hemispherical albedo when discussing photons (Hapke 1981, Eq. (41)). In the Appendix an approximate expression for $Y(i)$ is given which allows a more general expression for $y(g)$ to be used than that in Eq. (1).
FIG. 1. (a) Sputtering from a laboratory surface (an element of a grain). The ejecta leave at the angle $\theta_e$, where $Y(\theta_e)$ is the total yield for incident angle $\theta_i$. In the calculation we assume a single average $\theta_e$ for each $\theta_i$. (b) Picture in (a) applied to a spherical grain, $\phi$ is the phase angle (angle between incident ion and sputter ejecta). (c) Defines (i) the illumination angle of the surface of the regolith and (e) the exit angle.

For a plasma flowing onto a hemispherical surface or for a random flux of incident ions over the whole surface the net sputter flux averaged over the surface is obtained from the result in Eq. (2a) as

$$\Phi_i \approx \int_0^1 \Phi_0 (2 \cos(i) \, d\cos(i)) \, \bar{Y}(i) = \bar{Y}_r + \phi_0.$$  

(2b)

where $\phi_0$ is the integrated flux onto the surface. Therefore the total effective yield, $\bar{Y}_r$, is obtained by integrating Eq. (2a) (as in Eq. (2b)), giving

$$\bar{Y}_r \approx \left[ 1 - \frac{1}{4} \left( 1 - \frac{b}{4} \right) \ln 3 \right] \bar{Y}_s.$$  

(3)

This quantity is the bond albedo or bihemispherical reflection for single scattering in the language of light scattering, which for isotropic scatters is $-\bar{Y}_r/4$ (i.e., $w/4$; Hapke 1981).

Hapke (1986) has pointed out that for normal incidence on a surface composed of grains considerable reductions in the sputtering yield are predicted by Eq. (2a). For example, for $(1 \geq b \geq -1)$ in Eq. (1) then $0.25 \geq \bar{Y}(i)/\bar{Y}_s \geq 0.083$. In fact Hapke and Cassidy (1978) have found such reductions experimentally. Because of the enhancements, in Eq. (2a) at grazing incidence (cos(i) small), the total yield from a regolith in Eq. (3) exhibits somewhat smaller, but still important, reductions $(0.29 > \bar{Y}_r/\bar{Y}_s > 0.16)$ for the same range of $b$. In order to use laboratory data, $\bar{Y}_s$ and the appropriate $b$ are required for a single, roughly spherical, grain.

Sputtering yield measurements of monatomic (e.g., Andersen and Bay 1981) and molecular (e.g., Betz and Wehner 1983) refractory solids and some condensed gases (e.g., Johnson et al. 1984, Brown et al. 1984, Lancerotti et al. 1985, Gibbs et al. 1988) have been assembled. The laboratory sputter yields exhibit a dependence on incident angle in all cases of the form

$$Y_r(\theta_i) = Y_r(0) (\cos \theta_i)^{1/6}$$  

(4)

out to some angle $\theta_i$ where the yields rapidly go to zero because of surface roughness and reflection of the ions at grazing incidence. Typically $\theta_i \sim 70-80^\circ$.

There is, unfortunately, much less data for the dependence of the sputter yield on exit angle (e.g., Betz and Wehner 1983) and this dependence has not been measured for the condensed gases. The exit angle distribution will depend, in part, on the sputter mechanism. For tightly bound materials the momentum of the ion energizes the ejecta. For weakly bound materials (e.g., condensed gases) the energy deposited in the material collisionally can set in motion a large number of atoms or molecules resulting in large yields in which the direction of the initial momentum is not very important (Sigmund 1981). It has also been found that the electronic excitations and ionizations produced in the condensed gases can lead to ejection, electronic sputtering (Johnson and Brown 1982, Brown and Johnson 1986). For electronic sputtering, or for large yields of atoms, small molecules, or fragments due to collision cascade sputtering, the maximum in the ejecta will tend to be close to the surface normal for all incident angles. When it deviates from this, simulations for heavy-incident ions indicate that species are ejected (Fenyo et al. 1988) as if gas flows out along the path of the ion (Urbassek and Michl 1987). However, for low yield, tightly bound elements ejected collisionally (e.g., Betz and Wehner 1983) the incident momentum can produce an ejecta pattern which is off the normal away from the incident direction, in which case some memory of the incident momentum is retained. In fact, at grazing incidence, a single collision at the surface can eject an atom (Sigmund 1981). Interestingly, the electronic sputtering of a molecular organic solid by a heavy, very fast incident ion (Ens et al. 1988) can also lead to very large whole molecular ions ejected off the normal (the prompt ejecta).

Based on the above a variety of ejecta patterns are possible. Because the azimuthal dependence around the ejecta maximum is also complicated, we assume, for simplicity, that all the sputtered particles leave at some average angle $\theta_e$ from the surface normal as shown in Fig. 1a determined by the sputtering process involved. That is (Appendix)

$$\tilde{y}(g) = \frac{1}{2\pi} \int_0^1 Y_r(\theta_i) \delta(\cos g - \cos(\theta_i + \tilde{\theta}_j)) \times 2 \cos \theta_i \, d\cos \theta_i$$  

(5)
where \( Y_\theta(\theta) \) is given in Eq. (4), \( \theta \) is the phase angle (Fig. 1b), and \( \delta \) is the delta function.

Integrating the approximate yield in Eq. (5) over all phase angles gives the net, averaged single-grain yield of Eq. (1),

\[
\bar{Y}_s = \int_0^\pi Y_\theta(\theta) \, 2 \pi \, d \cos \theta = \int_0^\pi Y_\theta(\theta) \, 2 \cos \theta \, d \cos \theta. \tag{6a}
\]

This is also the average yield for a flat surface bombarded at random incidence. Using the expression in Eq. (4) in Eq. (6a) then

\[
\bar{Y}_s \approx 5 \cdot Y(0)(1 - (\cos \theta_c)^\alpha) = c \cdot Y(0). \tag{6b}
\]

where \( c = 1.7-2.5 \) for \( \theta_c = 70-80^\circ \). Therefore, the size of the critical angle for grazing incidence is important. In the following we use \( c = 2 (\theta_c = 74^\circ) \). Using Eq. (6b) in Eq. (3) the effective yield for a regolith, \( \bar{Y}_r \), can be compared to that yield which is typically measured, \( Y_r(0) (0.6 > \bar{Y}_r / Y_s(0) > 0.3) \).

Before applying the relationship between \( \bar{Y}_r \) and \( Y_r(0) \) we need to determine which value of \( b \) is appropriate for each surface composition. We write, for convenience, the average sputter ejecta angle in terms of \( \theta_c \), i.e., \( \theta_c = (x - 1) \theta_c \), where \( 1 \leq x < 2 \). Based on our earlier discussion \( x = 1 \) applies to the large yield case and \( x > 1 \) applies to the cases where the momentum of the incident ion is important. Now Eq. (5) can be integrated so that the phase function can be determined. That is, we would like to approximate the angular dependence determined from Eq. (5) by the form given in Eq. (1) which was used by Hapke (1981, 1986). This means that

\[
1 + b \cos g \rightarrow \frac{\sin(g/x)}{c x (\cos(g/x))^\alpha \sin \theta_c}, \quad \text{for} \quad g \leq (x \theta_c),
\]

\[
0, \quad \text{for} \quad g > (x \theta_c). \tag{7}
\]

where the results on the right are obtained by using Eq. (4) in Eq. (5).

It is clear from Eq. (7) that the simple form used in Eq. (1) is not a very good fit for the "phase function." However, because we are dealing with integrated quantities it is still useful. In Fig. 2 we compare the left- and right-hand sides of Eq. (7). (In comparing these, the sputtered particle distributions should really be smooth distributions with at least small contributions at all angles.) It is seen that, very crudely, \( b = 1 \) is more reasonable, on the average, for describing \( x \approx 1 \) as there is greater contribution in both cases from \( g < \pi/2 \). In the Appendix we obtain \( \bar{Y}_r / \bar{Y}_s \approx 0.34 \) for this case, close to the value of 0.29 for \( b = 1 \). Carey and McDonnell (1976) use microcraters for surface roughness and a cos \( \theta_c \) dependence. They obtain \( \bar{Y}_r / \bar{Y}_s \approx 0.3 \) for very rough surfaces. The \( b = 0 \) case (\( \bar{Y}_r / \bar{Y}_s = 0.21 \)) better represents \( x \approx 1.5 \) (\( \bar{Y}_r / \bar{Y}_s = 0.24 \), Appendix) and \( b = -1 \) (\( \bar{Y}_r / \bar{Y}_s = 0.16 \)) better represents \( x = 2 \) (\( \bar{Y}_r / \bar{Y}_s \approx 0.14 \), Appendix).

Based on the above discussion, for the large sputtering yields of small molecules (e.g., condensed gases on the icy satellites) \( b = 1 \) or \( x = 1 \), giving \( \bar{Y}_r = (0.6-0.7) Y_r(0) \). This result may be an underestimate as transients are seen in \( Y_r(0) \) upon irradiation of freshly deposited, low-temperature ice (Brown et al. 1980) because the surface becomes rough (e.g., Johnson et al. 1985, Strazzulla et al. 1988). The published yields for these materials are those after the initial transients have decayed, i.e., for a roughened surface, so that \( c \) may be somewhat larger for the ices. Therefore, the approximation of Sieveka and Johnson (1982), \( \bar{Y}_r = Y_r(0) \), is reasonable.

For tightly bound species with small yields (\( b = 0, x \approx 1.5 \)), then \( \bar{Y}_r = (0.5-0.4) Y_r(0) \) gives a more reasonable estimate of the effective yield. As the calculated sputter yields are generally quoted to be ~50% accurate, using a number between 1 and 0.4 times \( Y_r(0) \) to estimate the effective total yield, \( \bar{Y}_r \), is reasonable for describing the sputtering of a regolith. The larger reductions indicated by Hapke (1986) are for the special case of normal incidence to the planetary surface (e.g., fixed \( i \)).

The above results apply for total exposure (no shadowing of regolith) and only to the usual sputtering condition. That is, an ion incident on the surface of a grain ejects a bound species from the entrance surface. Transmission sputtering (Sigmund 1981) can also occur for very energetic ions (MeV) with the grains.
These ejected species are, of course, predominantly directed into the regolith. Sputtering by scattered ions near grazing incidence has been shown to affect surface morphology (Auciello and Kelly 1984) and can increase the amount of material ejected. Also, as Hapke (1986) points out, after a flux of ions sputters a surface containing more than one component for a long period of time, the yield is eventually dominated by those species which adsorb most efficiently to the regolith grains. Their yield will be determined by their adsorbed state on the surface of the grain (e.g., Hapke and Cassidy 1978, Hapke 1986, McGrath et al. 1986, Hunten et al. 1988) and not by their initial state in the solid. Clark et al. (1983) have shown that sputtering and sticking to neighboring grains is important in determining grain size in a regolith, hence, more detailed calculations of these processes are needed. The above results need to be confirmed experimentally. In the mean time they can be applied directly to typically planetary sputtering problems such as the magnetospheric plasma sputtering of the icy satellites in the outer Solar System.

Appendix. Evaluation of \( \overline{Y}(g) \). The quantity \( \overline{Y}(g) \) for a single grain is constructed such that

\[
\overline{Y} = \int_{-1}^{1} \overline{Y}(g) 2\pi d\cos g. \quad (A.1)
\]

As in Eq. (6a) for a laboratory sputtering yield \( Y(\theta_i, \theta_e, \phi_e) \) where \( \phi_e \) is the azimuthal exit angle, the sputtering yield for a spherical grain (viz., Fig. 1) is

\[
Y_s = \int_{0}^{1} \left[ \int d\theta \sin \theta \cos \theta \right] \overline{Y}(\theta_i, \theta_e, \phi_e)
\times 2 \cos \theta_i d\cos \theta_i. \quad (A.2)
\]

where the \( \cos \theta_i \) takes into account the flux relative to the surface normal. (Note that in obtaining \( Y(\theta_i, \theta_e, \phi_e) \) to use on a grain, surface curvature should be considered, e.g., transmissions sputtering at the edges). For the case we are considering in the text \( Y_s \) is

\[
Y_s(\theta_i, \theta_e, \phi_e) = \overline{Y}(\theta_e) \delta(\cos \theta_e - \cos \theta_e) \delta(\phi_e), \quad (A.3)
\]

where \( \delta(x) \) is the delta function (i.e., \( \int \delta(x) dx = 1 \), integral over all \( x \)). The single grain sputtering function is

\[
\overline{Y}(g) = \int_{0}^{1} Y_s(\theta_i, \theta_e, \phi_e) \delta(\cos g - \cos g')
\times 2 \cos \theta_i d\cos \theta_i d\cos \theta_e d\phi_e, \quad (A.4)
\]

where \( \cos g' = \cos \theta_i \cos \theta_e - \sin \theta_i \sin \theta_e \cos \phi_e \). Using the form for \( Y(\theta_i, \theta_e, \phi_e) \) in Eq. (A.3) gives the result for \( \overline{Y}(g) \) in Eq. (5).

Evaluation of \( \overline{Y}(i) \) and \( \overline{Y}_r \). The full transport equations for multiple scattering of particles or photons were used by Hapke (1981) to obtain some simple total reflectance expressions using the “phase function” (angular dependence) for single scattering given in Eq. (1). For the ion-induced sputtering problem discussed here we are only interested in single scattering as unit sticking efficiency applies. Therefore, a simple, approximate expression for \( \overline{Y}(i) \) can be used which can be evaluated for a more general \( \overline{Y}(g) \). The effective yield depends on the likelihood of striking the grain on the way in at a given angle \( (i) \) and exiting at an angle \( (e) \) without striking another grain (Fig. 1c). Therefore, for randomly distributed grains,

\[
\overline{Y}(i) \approx \int_{0}^{1} \exp(-n\sigma z(\cos i)) (n\sigma d/c(\cos i))
\times \int d\Omega_e \exp(-n\sigma z(\cos e)) \overline{Y}(g), \quad (A.5)
\]

where \( z \) is the depth into the regolith, \( n \) the grain number density, and \( \sigma \) the grain cross-sectional area. Integrating over \( z \) gives the simple expression

\[
\overline{Y}(i) \approx \int_{0}^{1} d\Omega_e \cos\theta_e \cos\theta_i + \cos\theta_i \overline{Y}(g), \quad (A.6)
\]

with \( \cos\theta_e = (\cos\theta_i \cos\theta_e - \sin\theta_i \sin\theta_e \cos\phi_e) \) where \( (i) \) is the illumination angle of the surface, \( (e) \) is the exit angle, and \( \phi_e \) azimuthal angle of exit. (Note that \( \theta_i \) and \( \theta_e \) are measured with respect to the local normal to the grain (Fig. 1b) and \( (i) \) and \( (e) \) with respect to planetary surface (Fig. 1c.).) The plus in Eq. (A.6) denotes only those directions out of the surface. For example, using the form in Eq. (1) in Eq. (A.6), then

\[
\overline{Y}(i) = \frac{\overline{Y}}{2} \left[ (1 - q_i \ln(1 + q_i^{-1})) + b q_i (0.5 - q_i + q_i^2 \ln(1 + q_i^{-1})) \right],
\]

where \( q_i = \cos(i) \). This is more complicated than Eq. (2a) but agrees for most \( \cos(i) \) and \( b \). Combining Eq. (A.6) with Eqs. (5) and (7) gives results for \( \overline{Y}_r/\overline{Y} \), in the range discussed in the text (0.34 for \( x = 1 \), 0.24 for \( x = 1.5 \), 0.14 for \( x = 2 \)).

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