Abstract

We combine laboratory and Apollo observations to describe the sputtering of the lunar surface and the composition of the ejecta with special reference to O. The atmospheric inventory appears to be dominated by micrometeorite vaporization of lunar grains. Sputtering effects are observable in the local plasma due to ion ejection, in the extended atmosphere through energetic neutral ejection, and on grain surfaces through the chemical fractionation of the redeposited sputter-ejecta. Ionization of the micrometeorite-vapor also contributes to the local plasma.

Introduction

Apollo data indicated that solar-wind ions created amorphous outer layers on lunar grains <0.02μm, changed these grains isotopically and chemically and the energetic-ions created tracks and spallation. These effects were used to estimate regolith turnover rates. Because solar wind-ions reach the surface, sputtering also occurs. We examine this here. Since micrometeorite bombardment modifies lunar grains (impact-glasses and agglutinates, Taylor 1982) and produces a vapor we compare it to sputtering. Sputtering by space plasmas and detection of ejected ions can determine the composition of surfaces by analogy with the laboratory technique SIMS (Secondary Ion Mass Spectrometry), as suggested for Saturn's moons (Johnson & Sittler 1990) and for the lunar surface (Stern 1991; Elphic et al., this issue). After describing the sputtering process we consider its application to the lunar surface and its importance relative to micrometeorite produced vapor, Fig. 1.

Laboratory Samples: Sputtering and SIMS

The sputtering yield of a species (number of ejected per incident ion) is roughly proportional to its surface concentration and inversely proportional to its binding energy, $U_i$. In this process neutrals are more readily ejected than ions and chemical-binding controls the ejecta composition (e.g. Johnson 1990). The yield depends only weakly on mass leading to slight preferential ejection of the lighter species (Kerridge & Kaplan 1978). For a molecular-solid the yield is fluence (exposure-time) dependent. In the laboratory, this dependence is partially due to projectile-induced surface structures. Only a fraction of the ion's energy goes into sputtering, most of it producing chemical alteration. After a fluence of $10^{17}$ ions/cm$^2$ (<1 year on the moon) every surface species has been struck and subsequent ions eject chemically-altered species. At high fluences sputtering proceeds stochiometrically (Johnson 1990). Three sputtering mechanisms occur. Electronic sputtering (by ions, electrons, or EUV-photons) results from excitation of electrons to repulsive states and, for refractory-materials, applies to adsorbed species ($H_2O$, Na). Sputtering by momentum-transfer is the dominant process for solar wind-ions. [Morgan & Shemansky (1990) suggest the O yields are due to electronic sputtering; the cross sections, $10^{-21}$ cm$^2$, are too small.] Finally, chemical sputtering arises after long-term bombardment or when bombarding with chemically reactive species ($H$, $O$, $C$). The total yield for oxides by low energy (0.1-10 keV), light ions (H, He) are similar to metals and peak near the energy-per-nucleon of the solar wind; $N_i$ peaks at 0.016 around 1.2 keV for $H^+$; for $He^+$, $Y = 0.2$ atoms/ion at 2 keV, close to that for $SiO_2$ seen in Fig.(1). Since the solar wind has 5% $He^+$, the contribution is of the same order as for protons. These yields increase with increasing angle of incidence having a maximum due to surface roughness. Normal incidence the ejecta distribution peaks toward the surface normal, a behavior also drastically affected by roughness. A decrease in the effective yield occurs for a porous-regolith due to redeposition Fig. 1. This can be estimated (Hapke 1986; Johnson 1989) from information on the ejected species and angles, and the sticking probabilities (Hapke & Cassidy 1978; Kasi & Rabalais 1990). The sticking of the ejecta results in a net transport into the regolith. Finally, the energy distribution of collisionally sputtered atoms peaks at $U_i/2$.

Emission of $H_2O$ (chemical-sputtering) has been observed in long-term H-bombardment and oxides; i.e. the formation of a volatile which is easily sputtered or desorbs thermally. In a hydrogen glow-discharge [Ishibe & Oyama 1979] this yield decreases with dose from 0.01 $H_2O/H$ to $0.003$, typical of physical sputtering, as the layer is reduced (depleted in $O$). Both physical and chemical sputtering lead to preferential ejection of oxygen [Thomas & Hofmann 1985] leaving microscopic metallic regions (Walters et al. 1989), a process possibly occurring on the Moon (Taylor & Epstein 1973).

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and can alter the near-surface composition by field-enhanced diffusion of oxygen and ionic impurities (alkalis in glasses, Pederson 1982). A fraction of the sputtered flux is ions, the basis for SIMS analysis. There is a large spread in the data for the ion fractions from oxides. The values for Mg, Al, Si and Ti oxides lie between 0.01 and 0.1 for keV Ar ion bombardment. For impurities the fraction depends strongly on their ionization potential implying large values for alkalis, \[ \alpha \cdot c_i \exp(-I_i/kT), \] where $I_i$ is the energy of species $i$ with concentration $c_i$; $T$ is an effective temperature, $T_{\text{eff}}$ (see also Elphic et al this issue). Ion fractions can drop when the surface oxide is reduced by sputtering due to neutralization from 'metal-islands' (Baragiola et al 1984). The ejected-ions are mostly atomic with average energies ten eV. Molecular-ions have low kinetic energies but the small yields are clearly resolvable [Elphic et al. this issue; for $\text{H}_2\text{O}$ absorbed on a silicate, $\text{SiOH}^+$ is observed, Nagai & Shimizu 1984]. Negative ions are also produced, the main one being $\text{O}^-$. Since ion yields are affected by surface-charging, usually positive, positive ion emission is favored [Baragiola et al 1990], the case on the sunlit face of the moon.

Lunar Sample Sputtering and the Atmosphere

Effective yields obtained from the analysis of lunar samples indicates that the amount of material ejected from a grain is of the order of the laboratory sputtering yield, allowing for microroughness and averaging over incident angle $\theta$ of 0.1-0.2$\text{A/yr}$, therefore, the grain is altered by this amount. This ejecta impacts neighbors with sticking probability depending on the species, producing a fractionated deposit. The direct ejecta is of interest to the atmosphere, $\sim 0.01-0.03\text{A/yr}$ consistent with estimates of McDonnell (1977). Some of this returns gravitationally. In addition, micrometeorite-vapor deposition reduces the net grain erosion. Zimmer et al (1977) and Kerridge (1990) place limits of $0.002-0.003\text{A/yr}$, well below the values above, suggesting that micrometeorite erosion is the dominant vapor-production process obscuring the sputter effect.

The loss of oxygen controls sputter aging of oxides, related to the relative importance of $0_2$, $\text{O}_2^-$, $\text{O}^-$ or $\text{O}^+$ in the ejecta. Low-energy $0_2$ may be returned to the positively charged surface inhibiting sputtering (Hecht et al 1989) or ballistic $0_2$ impacting the nightside may be converted to $\text{O}^-$ and swept away (Morgan & Shemansky 1990). However, directly ejected $0_2$ atoms are energetic ($U_2/2 > \text{keV}$) and predominantly escape, contrary to the suggestion of Morgan and Shemansky (1990). Since $0_2$ ejection involves lower energies it can be in thermal-equilibrium with the regolith. The efficiency of adsorption of returning $0_2$ is uncertain (Hapke 1986; Sprague, A.L. private communication) but it will likely react with the oxygen-depleted surface.

### Table 1 Composition of Grain

<table>
<thead>
<tr>
<th>Stoichiometry(1)</th>
<th>Decomposition(2)</th>
<th>Atmospheric Composition(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Na 1.0</td>
<td>Na 1.0</td>
</tr>
<tr>
<td>SiO2</td>
<td>K 0.025</td>
<td>K 0.25</td>
</tr>
<tr>
<td>Al 0.11</td>
<td>Fe 0.025</td>
<td>Fe 0.1</td>
</tr>
<tr>
<td>Ca 0.062</td>
<td>Mg 0.001</td>
<td>Mg 1.0</td>
</tr>
<tr>
<td>Fe 0.020</td>
<td>SiO2 0.001</td>
<td>SiO2 6.0</td>
</tr>
<tr>
<td>Mg 0.037</td>
<td>Mg 0.0006</td>
<td>Mg 4.0</td>
</tr>
<tr>
<td>Na 0.0033</td>
<td>Mg 0.0004</td>
<td>Na 4.0</td>
</tr>
<tr>
<td>K 0.00035</td>
<td>Mg 0.0004</td>
<td>K 4.0</td>
</tr>
</tbody>
</table>

Because of the dependence of sputtering and sticking on $U_i$, the ejecta can be dominated by a volatile species even if its concentration is low with the bombardment enhancing the diffusion of volatiles to the surface. Therefore, the effective concentration of species changes down to the depth of penetration of the ions 100A. If other regolith alteration/turn-over processes are slow, the surface concentration of the most volatile species (Na, K, Fe) will decrease until sputtering becomes proportional to the bulk atomic concentration (Johnson 1990). The time for attaining stoichiometric sputtering is determined by the time for sputter aging. However, if micro-meteorite vaporization is the dominant source of vapor then stoichiometric sputtering is not achieved. In Table 1, the decomposition-products from a grain heated to 1500K are compared to stoichiometric-loss. Although a non-equilibrium process, sputtering of neutrals is often characterized by an energy per atom of this order. Therefore, the neutral ejecta from a fresh grain should be similar to the decomposition data.

Since the regolith is an extension of the atmosphere, sticking/reaction coefficients control the atmospheric composition (Hapke & Cassidy 1978). In the structure of the neutral component, adsorb to the surfaces are also easily ejected by low energy protons. Therefore, even for a material with low Na concentration, Na can dominate the vapor (Hapke & Cassidy 1978). In Table 1 atmospheric-constituents are also given relative to Na calculated including adsorption in the regolith. Although Fe sputters easily, it is a minor component because it sticks well to the regolith. Reactive ion implantation can affect atmospheric composition: implanted C can produce CO, although there is no evidence for loss of implanted C (Kerridge & Kaplan 1978). Implanted H can produce H2 and H20 (Hodges this issue) and can replace Na in the lattice. Therefore, the atmospheric concentration of H(H2) is much smaller than expected.

The atmosphere has two spatial components; a small component of energetic neutrals with a largely partially or fully thermally accommodated component having a Maxwellian-like energy spectrum, as predicted by McGrath et al (1989). There is also a very small flux of backscattered, neutralized protons(H) with much larger energies. The directly sputtered species can have large escape fractions depending on $U_i$ [90% for O, Johnson 1990]. Ignoring escape for species with low $U_i$, the sputtered neutral atmosphere decays slowly for altitudes much less than a lunar radius $n(z)=(N/2Hc)(1+Z/Hc)^{-3/2}$, $Hc=(U/Mi)$ atmosphere the appropriate yield is -0.01-0.03A/yr. The directly ejected ions are a minor component having a Maxwellian-like energy spectrum, as predicted by McGrath et al (1989). This component has a large scale height 2Hc/3, whereas the accommodated component has a much smaller scale height determined by surface temperature, $H^2$ = (KT/MG). $n(z)=n(0)exp[-z/H]$. The sputtered ions follow trajectories determined by the local fields. Ions are also formed by photoionization, but the probability for a ballistic neutral is small ($10^{-2}-10^{-4}$, depending on the species). Therefore, ions from sputtered neutrals are not important [Fansten et al this issue]. Because of its larger contribution to the thermal regolith, the meteorite-produced vapor may be an important component of the local plasma. This vapor also permeates the regolith, so there are similar uncertainties in determining its contribution to the atmosphere. Assuming a net source $0.1A/yr$, with the ionization probabilities above, this source is comparable to the directly sputtered ions. Since ions of different energies are affected differently by the fields, the directly-sputtered-ions and the ionized vapor can be distinguished (Manka et al this issue). Using the mass spectra observed by a lunar orbiter with laboratory data, a map can be made of the concentration of surface species produced by sputtering or meteorite impact.

Conclusions

That solar-wind ions impact lunar grains is certain [implantation in and amorphous layers on grains, Taylor 1982]. Therefore, sputtering of lunar grains must occur. That micrometeorite impact grains [impact-glasses and agglutinates, Taylor 1982] and thereby produces a vapor is also certain (Morgan et al 1989). Micrometeorite impact also mixes the regolith and the vapor redeposited appears to be at least comparable to sputter erosion (Kerridge & Kaplan 1978) and is, possibly, the dominant source of lunar vapor. The sputter-produced vapor contains a larger proportion of atomic species and ions and we give the structure of the neutral component.

In sputtering of an oxide loss of oxygen plays a special role. Therefore the low value observed for atmospheric atomic oxygen is at first puzzling (Morgan & Shemansky 1990). When the photo-sputtering may apply to certain species, for oxygen momentum transfer and chemical sputtering are the dominant solar-wind-ejection processes. Oxygen is ejected as O, O2 or in an ionized form, being sensitive to the surface composition and charge-state. Therefore, oxygen is ejected energetically with a large escape fraction and returning O can react with the irradiation-altered surface.

The total sputtering yields are significant -0.1-0.2A/yr. A large fraction of this sputtered flux sticks to neighboring grains producing an effective yield 0.01-0.03A/yr. A small fraction also returns to the surface gravitationally. Therefore, in discussing solar-wind sputtering, the yield relevant to a particular measurement needs to be stated. For instance, for chemical-fractionation of deposits the relevant yield is -0.1-0.2A/yr, whereas the effective erosion rate of a grain is much smaller. When describing the direct-sputter contribution to the lunar atmosphere the appropriate yield is -0.01-0.03A/yr. The directly ejected ions are a fraction of this and are comparable in source strength to ionized meteorite-produced vapor. Comparing the time for sputter depletion to the regolith-turnover rate a variety of sputter-ages are possible and are found. However, if micrometeorite-produced lunar vapor coats the regolith (Kerridge 1990) stoichiometric sputtering...
is not attained over most of the lunar surface. Therefore trace volatile species will dominate the atmosphere.

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References


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