

SPUTTERING OF NA FROM THE LUNAR SURFACE: LABORATORY MEASUREMENTS Catherine A. Dukes and Raúl A. Baragiola, Laboratory for Atomic and Space Physics, University of Virginia, 395 McCormick Road, Charlottesville, VA 22904 (cdukes@virginia.edu or raul@virginia.edu)

Introduction: The lunar exosphere is strongly determined by surface processes such as photodesorption, solar wind sputtering, and thermal emission. In this tenuous, low-density ($\sim 10^4$ molecules cm^{-3} day and 2×10^5 molecules/ cm^{-3} night) atmosphere, each constituent molecule behaves separately from the rest, with very low probability of intermolecular collisions. Hence we can describe each atmospheric species as constituting a separate atmosphere. Multiple processes can contribute to the atmospheric budget: radioactive decay (e.g., Ar), solar wind species, gas vents, photostimulated desorption, thermal desorption, sputtering by solar wind, (Earth's) magnetospheric ions and cosmic rays, vaporization of projectile and surface during impacts by meteorites or comets. Volatile species may return to the atmosphere after a collision with the surface, whereas others will give only a transient contribution to the density. Numerous observations and models of lunar sodium have been done [1-6], providing information on the size, shape, and density of the Moon's exosphere.

In this study, we investigate the relative contribution of ion sputtering by solar wind or magnetospheric ions to the sodium atmosphere. Our studies complement laboratory work by Yakshinskiy and Madey [7] on desorption of alkalis deposited on top of SiO_2 surfaces by low energy photons and electrons, as well as laboratory studies by Elphic *et al.* [8] on simulated lunar soil irradiated by typical solar wind ions.

Experiment: To investigate solar wind sputtered ions and atoms, we performed a series of laboratory simulations irradiating lunar analogs with low energy helium, while measuring the mass spectra of the ejected secondary ions, neutrals, and their energy spectra [9]. The set of albite irradiation experiments were conducted under ultra-high vacuum conditions in a Physical Electronics 560 XPS/SAM system. In XPS the binding energy of an electron, ejected from a surface atom by a mono-energetic X-ray, is used to identify the atom, as well as its chemical bonding. Signal is provided by photoelectrons leaving the sample surface (< 50 angstroms) without energy loss.

Figure 1 shows a XPS photoelectron spectrum of albite, where we have identified the elements present on the grain surface: Na, Ca, Si, Al, O and C. Alkali impurities, i.e. Ca and K in albite, are due to random and non-random substitutions for Na in the interstitial regions between SiO_4 and AlO_4 tetrahedra. C is a normal surface impurity.

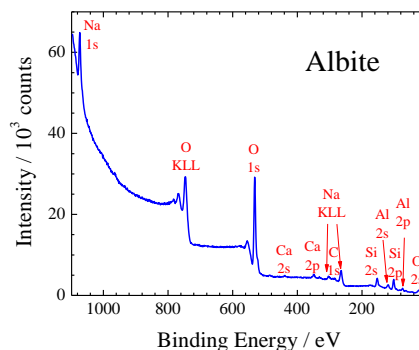


Figure 1: Representative XPS spectrum of albite obtained with Al-K x-rays. The Na-1s photoelectron peak at a binding energy of ~ 1072 eV was used to determine the amount of sodium present on the mineral surface.

Irradiations were done using 4 keV He^+ ions, rastered to insure uniform coverage. The UHV chamber pressure was maintained at 10^{-8} Torr (mostly He) during irradiation. Surface charge, which builds up quickly on the insulating minerals, was neutralized by a low energy electron flood gun during irradiation.

Results and Discussion: Since sodium sputtered from the Moon can redeposit as a coating by the action of gravity, as well as exist within a mineral lattice, we measured the depletion of sub-monolayer deposits of sodium on albite and olivine (powder or cleaved rock). Figure 2 shows the decrease of the sodium surface concentration with fluence.

Instead of a single exponential decay, the results can be fit to a double exponential decay. The initial decay is about two orders of magnitude faster than that of the intrinsic Na, with a depletion cross section of 9×10^{-16} cm^2 per atom. This cross section can be converted to a sputtering yield given the Na concentration at the surface. The second exponential decay is similar to that of the Na-containing minerals, with a cross section of $\sim 4.5 \times 10^{-17}$ cm^2 per atom for both olivine and albite samples. The equilibrium concentration at high fluences is more complex, as it consists of the original bulk concentration (zero for olivine) plus that resulting from diffusion during sodium deposition, as well as from deeper within the bulk (albite). Because the processes are time and fluence dependent, this decay cross section cannot be equated to a sputtering cross section.

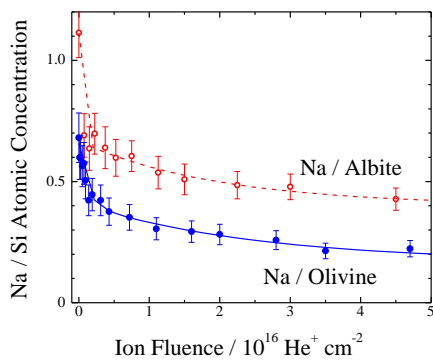


Figure 2: Na:Si concentration on a sub-monolayer of Na-deposited on ion-roughened albite rock and olivine powder vs. 4 keV He⁺ fluence. The Na:Si ratios are fit by a double exponential function plus a constant.

To investigate the charge and mass composition of the sputtered flux (from albite) we used a Stanford Research Systems RGA100 quadrupole mass spectrometer operated with the ionizer on, measuring neutrals and ions, or off, detecting only ions (Figure 3).

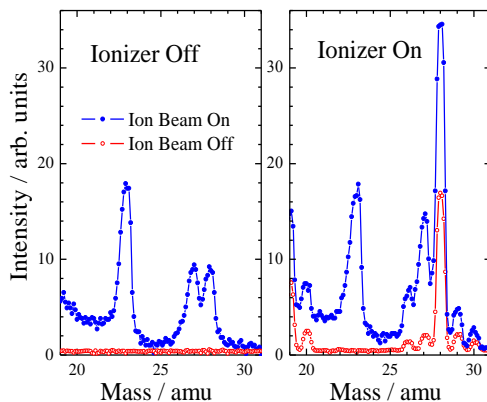


Figure 3: Mass spectra for 4 keV He⁺ on albite. (Left panel) No post ionization, solid dots show sputtered Na⁺, Si⁺, and Al⁺ with the ion beam on, while the open dots show only background with the ion beam off. (Right panel) Same as left panel but with post ionization in the mass spectrometer. With the ion beam on the sample, the signal is from sputtered ions and sputtered atoms, as well as background gas atoms.

The secondary ion spectrum clearly shows sodium (mass 23), suggesting that a significant fraction of sputtered Na is removed as an ion, as well as Al⁺ and Si⁺. No Na⁺ is ejected without the ion beam, and the Na⁰:(Na⁰ + Na⁺) ratio can be roughly gauged by comparing the peak heights with the RGA filament off to

that with the RGA filament on. Additional ionization in the mass spectrometer does not increase the Na signal, but that of other mass peaks derived from the vacuum chamber background gases.

The energy distribution of ions ejected by 4 keV He⁺ (Figure 4) peaks at ~4 eV for sputter equilibrated albite and ~6 eV for Na coated albite. The peak energies correspond to velocities of ~3 km/s and ~5 km/s, respectively, for a single Na ion. This implies that for the lunar surface, which has an escape velocity of ~2.4 km/s, most of the sputtered ions will leave the lunar environment. Only the small fraction of sputtered Na ions below the escape velocity will remain within the lunar exosphere.

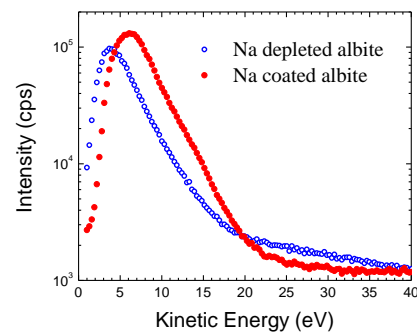


Figure 4: Secondary ion energy spectra ejected by 4 keV He⁺ for sputter equilibrated albite and Na-coated albite.

Conclusion: The major results of this study are: the absolute value of sputtering cross sections ($\sigma_s \approx 1 \times 10^{15} \text{ cm}^2 \text{ atom}^{-1}$), the predominance of ions in the Na sputter flux and the similar results for different Na-bearing minerals. Even though we report results only for Na, it is important to note that all elements are ejected, and, therefore sputtering will contribute to the abundance of the different species present in exospheres of the Moon or Mercury.

Acknowledgements: This work was supported by the NASA Cosmochemistry (NNX08AG72G) and the NSF Astronomy (AST0807830) programs.

References: [1] Mendillo *et al.* (2001) *Earth, Moon and Planets* 85-86, 271-277. [2] Hunten and Sprague (1997) *Adv. Space Res.* 19, 1551-1560. [3] Killen and Ip (1999) *Rev. Geophys.* 37, 361-406. [4] Stern (1999) *Rev. Geophys.* 37, 453-491. [5] Potter *et al.* (2000) *J. Geophys. Res.* 105, 15073-15084. [6] Nemtchinov *et al.* (2002) *Int. J. Impact Engn.* 27, 521-534. [7] Yakshinskiy and Madey (1999) *Nature* 400, 642-644. [8] Elphic *et al.* (1991) *Geophys. Res. Lett.* 18, 2165-2168. [9] Dukes and Baragiola, (2010) *Icarus* (submitted).