Ice in the Polar Regions of the Moon

L. J. Lanzerotti and W. L. Brown

Bell Laboratories, Murray Hill, New Jersey 07974

R. E. Johnson

Department of Nuclear Engineering and Engineering Physics, University of Virginia, Charlottesville, Virginia 22904

Recent laboratory measurements of the erosion of H₂O ice are used to estimate the loss rates of possible ‘trapped’ volatiles in the cold lunar polar regions. We conclude that a significant accumulation of water ice is unlikely to occur.

Arnold [1979] recently called attention to the fact that a significant paper by Watson et al. [1961] on the possible presence of water ice in the lunar polar regions had been neglected by the relevant scientific community. Watson et al. [1961] pointed out that a large portion of the lunar polar regions has been completely shadowed from direct sunlight for a long time. The potential ‘cold traps’ have extents of ≥1 km and temperatures <120°K. Arnold [1979] used the work of Watson et al. [1961] to reassess the possibility of water ice in the polar regions of the moon. He conducted a thorough reexamination of possible source, transport, and loss mechanisms for water on the lunar surface and in the potential traps. Based on the reevaluation, Arnold concluded that the question of the presence of H₂O in the polar traps remains open.

One of the important water loss mechanisms considered by Arnold was that of the sputtering of water ice from the lunar polar surfaces by the solar wind. He concluded that the information available to him at the time of writing of his paper was insufficient to assess in a definitive way this loss process. For many situations of astronomical interest, sputtering is an important process because of the low yields per incident particle. Our recent laboratory experiments on the sputtering of water ice by energetic particles [Brown et al., 1978, 1980] have shown, however, that the erosion of such ice is much more efficient than would be expected on the basis of conventional sputtering theory [Sigmund, 1969]. We find, for example, that the erosion coefficient S for water ice by ~100-keV protons is ~2 molecules per incident ion and decreases to ~0.8 for ~6-keV and ~0.15 for ~1.5-MeV protons. For helium ions, approximately a 5–10% constituent of the solar wind and solar energetic particle flux, S is ~7 to 8 times larger than the yield for protons at the corresponding velocity. The erosion yields S are very nearly proportional to (dE/dx)² [Brown et al., 1980], where (dE/dx) is the ionization production per unit depth into the material [Haff, 1976; Brown et al., 1980]. At the lowest energies of interest here, the contributions from conventional collisional sputtering can begin to become a factor as well [Brown et al., 1980]; S is approximately unity for a 1-keV proton on water ice.

Lanzerotti et al. [1978] used early laboratory erosion yield results [Brown et al., 1978] to estimate the erosion rates of ice grains by the solar wind and solar cosmic rays. They conclude that beyond ~1.5 AU the grain lifetimes were determined essentially by the sputtering process rather than by sublimation.

Sources of ions incident on the lunar polar cold traps include the same sources discussed by Lanzerotti et al. [1978] as well as ions in the tail of the earth’s magnetosphere.

The directional nature of the solar wind flow means that these ions can certainly be screened by appropriate features of the lunar landscape in the polar regions. In those regions that might be exposed to these ions, the low angles of incidence α (α ≅ 0 for grazing incidence) will decrease the effective incident particle flux as sin α. However, the erosion yield per particle can be expected to increase with decreasing α (as the cosec of α) resulting in yields nearly independent of angle. Using a solar wind flux of 2 × 10⁶ particles (cm² s⁻¹) with a mean energy of 1 keV per amu, the erosion rate in an exposed area will be ~10⁻³ molecules (cm² s⁻¹) (Figure 1). A 5% He abundance in the wind would increase this value by ~15%. We note from the sublimation line in Figure 1 that the lunar cold traps would have to have temperatures <105°K in order for sublimation not to dominate the loss mechanisms (see also Arnold [1979]).

Lanzerotti et al. [1978] estimated that the effect of one nominal solar flare event per year on icy grains produced an average water loss of ~2 × 10⁶ particle cm⁻² s⁻¹. The number of solar cosmic ray events is highly variable (a factor of 10 or more) from year to year during the solar cycle. The erosion by one solar particle event is shown in Figure 1.

The fluxes of low-energy (≥50 keV) ions in the interplanetary medium that arise from solar active regions are much more prevalent than the occurrence of individual cosmic ray events, although the active regions ions are of lower intensities. For example, Von Hollebeke et al. [1978] show the intensity of corotating interplanetary particle fluxes to be ~10⁻³ (cm⁻² s⁻¹ MeV⁻¹) for ~1-MeV protons. These fluxes of particles usually have a great degree of isotropy in interplanetary space.

These corotating events typically have steep energy spectra and last for a few days [e.g., Von Hollebeke et al., 1978]. If we take dJ/dE ~ E⁻², then J(> 10 keV) ~ 4 × 10⁶ protons cm⁻² s⁻¹. If a typical occurrence rate is of the order of two events per solar rotation (~27 days), then the interplanetary space is filled with such particles about a third of the time. In this case, the average erosion is ~3·10⁻¹ molecules (cm² s⁻¹) (Figure 1), or somewhat higher if the alpha particle to proton ratio is ~5% [e.g., Lanzerotti and Macelennan, 1973; Stroscio et al., 1976].

The efficiency of these ions as an erosion mechanism is enhanced by the fact that they can have reasonably ready access to the magnetosphere tail and are reasonably isotropic there as well. The isotropy means that no lunar topography would...
The eroded particles are expected to be ejected with average energies in the range 0.1–0.6 eV. Such energies are too small to permit escape from the lunar gravitational field, but they do correspond to mean jump distances along the lunar surface of ≥500 km for H$_2$O molecules, a much larger distance than for thermally ejected particles at the temperatures expected in the cold traps. Since these jump distances are large compared to the sizes of the postulated cold traps, ion erosion will be an effective loss mechanism for lunar ice. The total water ice erosion rate from the various omnidirectional interplanetary and magnetosphere fluxes is of comparable magnitude to the deposition rate of one molecular H$_2$O layer per year (≈10$^{-5}$ molecules (cm$^2$ s$^{-1}$)) as estimated by Arnold [1979] in considering the various water source mechanisms. Therefore we believe a significant accumulation of water frost is unlikely, even in the coldest lunar polar regions which are permanently shadowed from sunlight.

REFERENCES

Haff, P. K., Notes and comments on sputtering, Caltech Band Aid preprint, March 1976.

(Received July 28, 1980; revised November 17, 1980; accepted December 5, 1980.)