



Monte Carlo simulations of the exospheric transport of cometary volatiles on the Moon

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Permanently shadowed regions (PSRs) are areas of a planetary surface that lie in continual shadow from direct sunlight. Their existence at the lunar polar regions has been recognized for nearly 70 years [1] and in the intervening time much has been learned about their unique thermal environment and capacity for volatile preservation [2]. In the absence of direct sunlight and without an atmosphere to transport and trap heat, lunar PSRs remain cold throughout the year, with maximum temperatures typically below ~ 110 K, although temperatures as low as 45 K have been reported in some areas [3]. At these low temperatures, PSRs can act as cold traps for H₂O water ice as sublimation rates are negligibly low (~ 1 mm Gyr⁻¹).

In addition to H₂O, other volatile species, such as CO₂, NH₃, H₂S, SO₂, and CH₄ are regularly supplied to the Moon through cometary impacts or are created through solar wind interactions. These species have been observed in varying abundances by the Lunar CRater Observation and Sensing Satellite (LCROSS) experiment within Cabeus crater near the south pole [4]. Once delivered or produced, these molecules may migrate about the lunar surface through a series of ballistic hops and potentially accumulate within cold traps near the poles if temperatures are sufficiently low. Relative to H₂O, however, these volatiles have higher vapor pressures and thus require lower temperatures for long-term thermodynamic stability; thus, not all volatiles detected in the LCROSS plume are expected to be cold trapped in the current lunar thermal environment. CH₄, for example, which has been detected in the lunar exosphere [5], is stable at temperatures below ~ 25 K [6], which is too low to be cold trapped, although it can be adsorbed on the surface. Other volatiles, in contrast, such as CO₂, are stable at relatively higher temperatures ($T_{\text{max}} < 55$ K) and potentially accumulate within the coldest regions of permanent shadow. Observational evidence for CO₂ frost has recently been provided by the Lyman Alpha Mapping Project (LAMP) instrument on the Lunar Reconnaissance Orbiter (LRO) [6]. Although Diviner temperature data do not indicate significantly large regions where CO₂ is stable, micro cold traps (at cm scales) will provide additional cold trapping area.

Modelling the diurnal and seasonal migration patterns of different exospheric volatiles can shed light on geotemporal trends in volatile dispersion and cold trapping [7, 8, 9, 10], and may additionally aid in the interpretation of orbital remote sensing data. In this work, we use a Monte Carlo model to simulate the ballistic migration of the aforementioned cometary volatiles to understand differences in their migration, destruction and cold trap capture. The model utilized here

is similar to that described in Kloos et al. [11]. Individual molecules of a given volatile are placed on the surface at non-polar latitudes (equatorward of $\pm 80^\circ$) using a randomized production scheme. The molecule is assumed to achieve instantaneous thermal equilibrium with the lunar regolith and acquire the local surface temperature. For surface locations equatorward of $\pm 80^\circ$, temperatures are obtained using global, topographically resolved Diviner temperature maps [12]. Due to the slight obliquity of the Moon ($< 1.59^\circ$), however, the polar temperatures can vary significantly throughout the year. Thus, we have updated the model to include the recently available seasonal Diviner polar temperature data created by Williams et al. [13]. These maps enable more realistic simulations of the ballistic polar migration than that reported by Kloos et al. [11].

To calculate the adsorption residence time, τ , for a molecule, we use the relationship defined by Langmuir [14]:

$$\tau = (1/v_0)\exp(E_a/k_B T_{\text{surf}}), \quad (1)$$

where v_0 is the vibrational frequency, E_a is the activation energy and T_{surf} is the surface temperature. The variables v_0 and E_a are obtained for each volatile using data from Sandford and Allamandola [15]. Once molecules are released, they inherit a velocity vector using three-dimensional cartesian coordinates, where the vector direction is randomized and the speed is drawn from an Armand distribution. Molecules ejected outward from the surface may be photodissociated through interaction with solar UV photons. Photo-destruction rates for each species are determined using data compiled by Huebner et al., [16], derived for normal sun activity. The effects of surface roughness, which may delay the pole-ward migration of molecules by increasing the number of hops at a given location, are incorporated into the model and we quantify these effects on the velocity distribution for different volatile species.

Figure 1 shows the north and south geographic delivery patterns for H_2O , where the y-axis gives the PSR particle concentration σ_p normalized by the production rate γ . It is found that the north/south asymmetry in PSR capture reported by Kloos et al., [11] persists using the updated Diviner polar temperature data. The bulk majority ($\sim 82\%$) of H_2O molecules are destroyed through photolysis, while the remaining are cold trapped in PSRs ($< 1\%$ achieve escape velocity). Results for other volatile species will be available by the commencement of the conference.

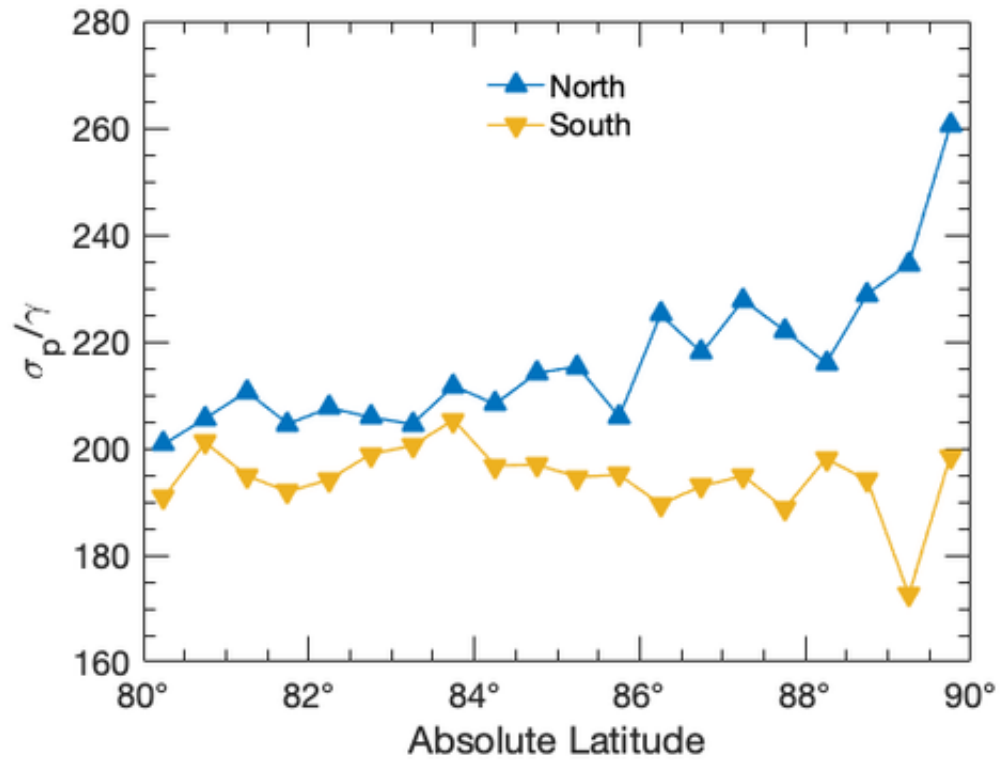


Figure 1. Geographic trends in PSR-capture of H₂O molecules.

References

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