

Introduction: Understanding the origin, abundance and distribution of water and other volatiles on the surface of the Moon is integral to both understanding the history of the inner solar system and characterizing the in situ resources available for planetary exploration. Motivated in part by these questions, there is widespread interest in visiting the lunar surface over the next decade, particularly permanently shadowed regions (PSRs) near the lunar poles. However, any soft landing on the lunar surface will almost inevitably involve the release of non-indigenous volatiles when spacecraft fire their thrusters during descent. Exhaust species may include H₂O, CO₂ or NH₃, which have been detected in least one polar cold trap [1].

This work focuses on the question of how exhaust gases may influence measurements of exospheric and surface volatile abundance, particularly in the polar environment. Specifically, we examine (i) how exhaust gases are distributed in the vicinity of the landing site, (ii) how long they persist in the polar environment, and (iii) the implications for measurements made by lander-based instrumentation.

Method: We model the transport of exhaust volatiles using the Direct Simulation Monte Carlo method [2], which simulates gas dynamics by tracking the motion of a large number of representative molecules, accounting for the transfer of momentum and energy between molecules through collisions in regions where the gas is sufficiently dense. Initial gas density, velocity and temperature in the vicinity of the nozzle exit are derived from analytical expressions [3], based on the combustion characteristics of hydrazine [4]. To begin with, we consider the vertical descent phase towards the end of a

landing trajectory, assuming representative propulsion system characteristics. Surface temperatures of representative of both PSRs and illuminated polar terrain are considered. Volatile losses due to thermal escape and photolysis are modeled, and molecules that collide with the surface are assumed to have a mean surface residence time that depends on local surface temperature and desorption activation energy.

Initial Results & Discussion: Recently, we modeled the *global* transport and deposition of the of the water vapor component of spacecraft exhaust during a nominal high-latitude (70° S) landing [5]. Figure 1 illustrates the sensitivity of exospheric evolution and surface deposition patterns to desorption activation energy. Building on this work, we plan to investigate the propagation of NH₃, N₂ and H₂ (hydrazine fuel combustion products), focusing on the evolution with time of exospheric and surface density at the scale of a lander. All of these species are more volatile than water, with estimated desorption activation energies of 0.3 eV, 0.2 eV and 0.01 eV respectively [6,7], such that N₂ and H₂ remain mobile at polar temperatures, while NH₃ may adsorb for a third of a lunar day at a nominal PSR temperature of 80 K, with implications for mission planning and measurements that aim to characterize the extant lunar volatile inventory.

References: [1] Colaprete et al. (2010), *Science*. [2] Bird, G. A. (1994), *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*. [3] Roberts, L. (1966), *Fluid Dynamics Aspects of Space Flight*. [4] Lee, K. H. (2017), *PLOS One*. [5] Prem et al. (2020, under review). [6] Sandford & Allamandola (1993), *Ap. J.* [7] Grunze et al. (1984), *Phys. Rev. Lett.*

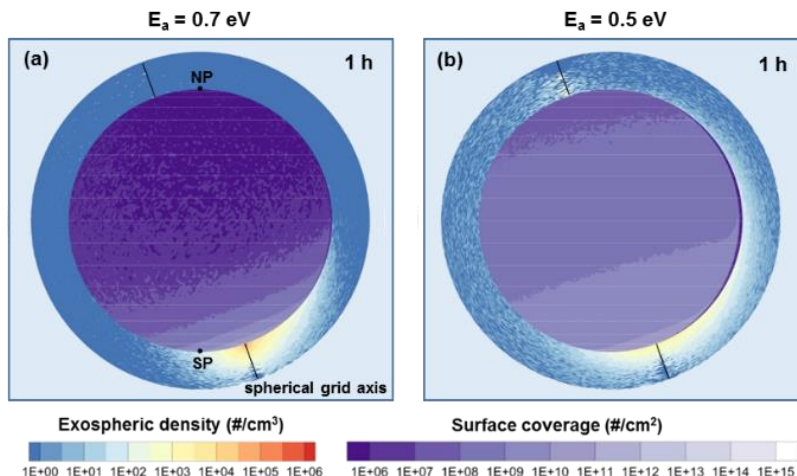


Figure 1: Exospheric density (up to an altitude of 500 km) in the plane of descent, and night-side surface coverage, one hour after a simulated high-latitude (70° S) lunar landing. These simulations assumed desorption activation energies of (a) 0.7 eV and (b) 0.5 eV for water molecules. Note that the apparent “gap” in exospheric density along the spherical computational grid axis (indicated by the solid black line) is a visualization artefact.