UPPER LIMITS ON THE PROPAGATION OF CONSTITUENTS OF THE CHANG'E-3 EXHAUST PLUME FROM LADEE OBSERVATIONS.

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Introduction: The native lunar exosphere is sparse. The estimated total mass of the lunar exosphere is ~10^7 g, with a source rate of ~10 g/s [1]. Landing a vehicle such as the Chinese Chang'e-3 lander on the surface of the Moon would require burning an estimated 10^6 g of rocket fuel over ~12 minutes. Thus, the introduction of vapor into the lunar environment via rocket exhaust during a soft lunar landing constitutes a 100 times temporary enhancement to the source rate to the lunar exosphere and an increase in the total mass of 10%. Whereas the native lunar exosphere is comprised primarily of helium and argon; the rocket exhaust comprises water, carbon dioxide, ammonia, and other HCNO products.

The distribution of particles in the lunar exosphere is largely controlled by the interactions between the particles and the lunar surface. For example, helium does not stick to lunar regolith grains, thus follows an inverse relationship between the density and the surface temperature [2]. In contrast, argon does stick to the surface at colder, nightside temperatures. Argon density is observed to peak at the terminators [3]. Thus, if the propagation of the exhaust vapors can be monitored, it can reveal previously unknown properties of the gas-surface interaction with the lunar regolith.

We model the release and propagation of the exhaust gases on the Moon and compare to observations in orbit around the Moon from the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft.

Exhaust Profile: We assume the lander burned fuel at a rate of 1.5 kg/s with an exhaust velocity of 3000 m/s during its descent from lunar orbit to the surface. The descent occurred over 12 minutes, beginning at 15 km altitude. The direction of the burn was initially tangent to the Moon, or in the direction of the orbital motion of the spacecraft at periapsis during its 15 km x 100 km staging orbit. During this burn, the combined orbital velocity and exhaust velocity (1.7 km/s + 3.0 km/s) well exceeds the escape velocity of the Moon, 2.3 km/s. Therefore we focus the simulations on the exhaust released once the attitude of the thrusters was pitched over, i.e., the final 3 km altitude of the descent [4]. Chang'e 3 landed in Mare Imbrium at the coordinates 44.1214° N and 340.4884°E at approximately at 0815 lunar local time.

Propagation Model: The Monte Carlo Exosphere model was developed for the lunar exosphere [5] and previously applied to the evolution of the vapor plumes from the impact of LCROSS [6]. The model follows the equation of motion for a set of test particles under the influence of gravity.

Surface interactions are accounted for by assigning parameters to approximate sticking to the surface and thermalization. The sticking module assumes a temperature-based sticking function that varies with species. Particles that stick are given a probability of release once the surface area rotates to a warmer longitude. The thermalization module assigns the energy of a particle leaving the surface using an equal weighting to the incident energy and the energy using a velocity taken from the local thermal distribution.

Particles are followed until they reach the Hill sphere at 37 R_{moon} or until they are photodissociated by sunlight, using probabilities given in [7]. Water molecules stick to the nightside and are rereleased when they rotate back into sunlight at dawn. Other molecules are assumed not to condense on the lunar surface.

Simulation Results: The simulations follow water (H_2O), molecular nitrogen (N_2), and other, more minor, molecules released as byproducts of the burning of dinitrogen tetroxide (N_2O_4) and mono-methyl hydrazine (CN_2H_6). First, we investigate the density as a function of time for the simplified case of the instantaneous release of the exhaust from the landing site. The particles are binned as a function of time in a spherical grid with logarithmic spacing in altitude and equal spacing in latitude and longitude. We examine the density in the equatorial latitudes at a constant altitude of ~50 km. None of the modeled constituents has the same density profile owing to their different masses, photodissociation cross-sections, and interactions with the lunar surface.

Molecular hydrogen goes global within an hour of release in the latitude and altitude range considered owing to its low molecular weight (Fig. 1). The density is shown on the color scale, which has the units of particles/cm^3/kg of that material released. Therefore the expected density is obtained by multiplying the value by the expected released mass of this constituent. Molecular hydrogen persists at low levels for hours following the release owing to its long lifetime against photodissociation. In contrast, the short lifetime to photodissociation of ammonia causes it to disappear from the dayside within 4 hours. A small portion of ammonia lingers in the coldest part of the nighttime exosphere at pre-dawn longitudes afterwards.

Water, which condenses on the nightside, shows its highest concentrations at ~50 km altitude on the dayside in the morning quadrant (Fig. 2). The density uses the same color scale as in Fig. 1. For carbon dioxide, highest densities also occur on the dayside at this altitude range. However, the scale height is smaller on the nightside owing to the lower surface temperature there. At lower altitude, carbon dioxide has highest density in the pre-dawn sector unlike water.

LADEE Data: LADEE is in a retrograde orbit with an inclination of 22° about the equator. Perilune occurs close to the dawn terminator at altitudes between 20-60 km. Apolune altitudes vary between 60-150 km. Thus, the latitude range displayed in the model results was selected to be comparable with LADEE observations. Although the altitude of LADEE changes as it sweeps in longitude, the initial model results are shown at a constant altitude range spanning 35 km to 57 km.

On the day of the Chang'e-3 landing, the Neutral Mass Spectrometer (NMS) acquired data for two orbits prior to the landing and on 4 of the orbits after the landing. Relevant data were also acquired during one orbit on the day following the landing. On a given orbit, the NMS is turned on just after passing noon lunar local time and acquires in situ measurements of the neutral density throughout the morning side until lunar local midnight. To compare LADEE NMS data with the model results, LADEE flies through the simulations in Figs. 1-2 from right to left, cycling through the entire longitude range every < 2 hr. However, the NMS is only turned on between 180°-360°.

Conclusions: Model results are extremely sensitive to the assumed surface interactions. In particular, because the exhaust gases have such a large initial velocity, the degree to which the molecules thermalize on contact with the regolith modulates the subsequent propagation of exhaust gases. Without full thermalization, the bulk of the exhaust gases will escape the Moon on the first hop off of the lunar surface. We will present the comparisons between the models and the observations. Determining upper limits to the amounts of each exhaust byproduct observed by LADEE, we will determine the amount of thermalization in the model required to agree with the observations. Therefore, LADEE will utilize volatiles constituents released during the Chang'e-3 landing on the Moon to determine surface-exosphere interactions of non-native species to the lunar environment. This opportunistic observation adds to the planned scientific return of the LADEE mission.

References: [1] Stern S. A. (1999) *Rev. Geophys., 37,* 453–491. [2] Hodges, R. R. (1973) *JGR 78*, 8055-8064 . [3] Hodges, R. R. (1975) *Moon 14*, 139-157. [4] Kremer, K. (2013) *Universe Today, Dec. 20*. [5] Crider, D. H. and Vondrak, R. R. (2000) *JGR 105*, 26773-26782. [6] Hurley, D. M. (2011) *JGR 116*, E10007. [7] Huebner W. F. et al. (1992) *Astrophys. Sp. Sci. 195*, 1-294.

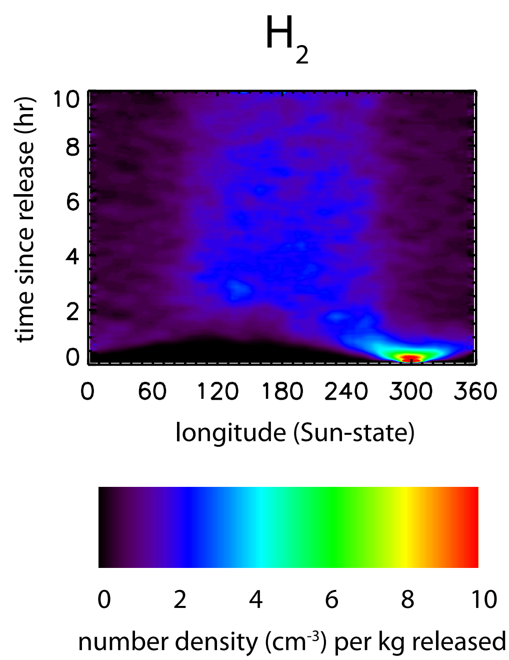

Fig. 1. Modeled temporal evolution of H_2 density at 35-57 km altitude within 30° of the equator after the release of H_2 in the exhaust plume from a lunar lander.

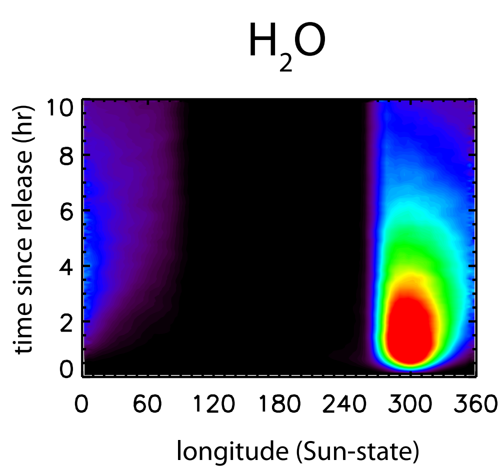

Fig. 2. Modeled temporal evolution of H_2O density at 35-57 km altitude within 30° of the equator after the release of H_2O in the exhaust plume from a lunar lander.