TRANSPORT OF WATER IN A TRANSIENT IMPACT-GENERATED LUNAR ATMOSPHERE.

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Introduction: Over the years, several missions have detected signs of water and other volatiles in permanently shadowed craters (cold traps) near the lunar poles [1,2,3]. Comet impacts are thought to have delivered significant quantities of these volatiles [4], but questions remain as to how much, and why volatile abundance appears to vary between different regions of permanent shadow [5,6]. We use numerical simulations to investigate the physical processes governing volatile transport in the transient atmosphere generated after a comet impact, with a focus on how these processes influence the accumulation of water in cold traps.

Simulating the fate of cometary volatiles is a challenging task, primarily due to the range of spatial and temporal scales involved. For instance, a comet 1 km in radius can generate a post-impact atmosphere that extends out to 60,000 km from the Moon. Similarly, a majority of the impact vapor escapes lunar gravity within seconds, but a significant part lingers for months. Besides the range of scales, there are a number of physical processes to be accounted for: photochemistry, radiation, shocks, winds and other phenomena.

Previous work has studied impacts in the short term [7] and transport processes in the collisionless limit [8,9], where the atmosphere is so thin that individual molecules do not interact, simply undergoing ballistic hops until capture. The collisionless approximation is valid in the tenuous exosphere that exists months after impact, when most cometary water has been lost or captured, but it cannot resolve the transient winds and shock structures that have a strong influence on where, and how much, water is captured. Our method can track cometary water from impact to capture, allowing us to study the dynamics of the transient atmosphere in detail and offering a different view of post-impact volatile transport on a normally airless body.

Numerical method: We adopt a hybrid approach [10] to modeling impact delivery of lunar water, using the SOVA hydrocode in conjunction with the Direct Simulation Monte Carlo (DSMC) method. The immediate physics of the impact are simulated using SOVA, which solves for the hydrodynamic flow of molten/vaporized target and projectile material. Presently, the comet is modeled as a sphere of water ice, 1 km in radius, while the lunar surface has the properties of dunite. The results discussed here are for an oblique impact (oriented 60^o from the horizontal) at 30 km/s. Subsequent modeling of the vaporized projectile material is carried out using DSMC, a statistical method that models gas dynamics by moving and colliding a representative number ($O(10^7)$) of simulated molecules within a gridded domain. Our DSMC code is parallelized for computational speed and includes variable gravity, a simple, diurnally varying surface temperature map and temperature-dependent residence times for water molecules that land on the lunar surface. Seven regions of permanent shadow are specified, and any molecule that lands in these regions is assumed to be permanently cold-trapped. Both SOVA and DSMC simulations are unsteady and three-dimensional. In addition, the molecular approach readily allows us to model photo/chemistry and radiative heat transfer.

Results and discussion: Our baseline simulations model radiative cooling of water and photodestruction of molecules in sunlight, but neglect photochemical products and reactions, as well as any radiative heating of lofted water vapor by the lunar surface. Here, after summarizing our baseline results, we re-examine some of the simplifications made and discuss implications for retention and transport of cometary water.

Transient atmospheric dynamics: Upon impact, the comet vaporizes, generating a cloud of water vapor that expands rapidly into vacuum. Much of this vapor escapes in seconds, but ~20-30% remains gravitationally bound as a collisional, transient atmosphere. Within hours, vapor begins to fall back to the lunar surface. Water molecules landing on the cold lunar night-side are largely immobilized until sunrise. In contrast, molecules falling back to the warm day-side have much shorter residence times, giving rise to a relatively dense day-side atmosphere. Global pressure gradients drive day-side winds, which carry vapor to the night-side. Meanwhile, the re-convergence of expanding vapor antipodal to the point of impact forms a shock structure that channels vapor to the surface, causing preferential deposition around the antipode (Fig. 1).

The atmosphere only transitions to the collisionless limit after months. At this stage, shocks and pressure-driven winds dissipate, but sublimation of night-side frost at sunrise continues to sustain localized flow across the dawn terminator. Ultimately, all gravitationally bound water is photodestroyed or captured. We find that, seven days after a 60^o, 30 km/s impact (deposition continues for months beyond this), the cold traps have accumulated water sufficient to form ice deposits O(1 mm) thick over an area of 5832 km^2.

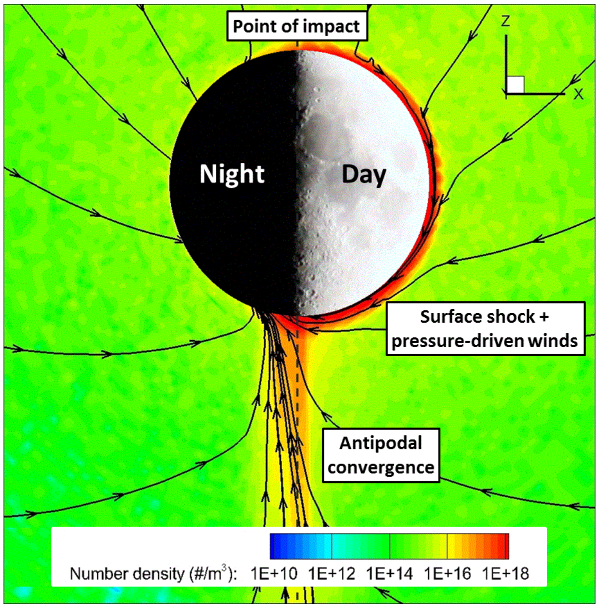

Fig. 1. Contours of number density (six hours after a 60°, 30 km/s impact at the north pole) with streamlines superimposed. Characteristic features are marked.

Self-shielding: The primary loss process for gravitationally bound water is photodissociation. Our baseline simulations assume the atmosphere to be optically thin at all times i.e. all molecules outside the Moon's shadow are susceptible to dissociation. In reality, the atmosphere is sufficiently thick that lower layers are shielded from sunlight. To model this, we perform periodic calculations of atmospheric column density, accounting for changes in atmospheric structure and the Sun's relative position. The intensity of sunlight (and thereby, the photodissociation rate) is attenuated accordingly. More strongly illuminated parts of the vapor cloud are thus preferentially depleted, and the overall rate of photodestruction is reduced, allowing the cold traps to capture a greater fraction of water.

Photochemistry: While our baseline simulations ignore photodissociation products and reactions, chemistry is the chief determinant of the long-term composition of an impact-generated atmosphere [11]. Calculations using a simple, analytical photo/chemistry model confirm the significance of photo/chemical reactions over simulation time scales. Two notable consequences are that: i) recombination reactions replenish some of the water lost to photodissociation and ii) non-condensable species (such as O_2) accumulate, tending to inhibit condensation of water into cold traps.

Radiative heating: The lunar day-side reaches temperatures of ~400 K and thus, radiates strongly in the far infrared. The water vapor atmosphere can absorb a significant part of this radiation. Calculations indicate that within much of the post-impact atmosphere, far infrared radiation from the Moon is stronger than that from the Sun (Fig. 2). Over the time scales for which

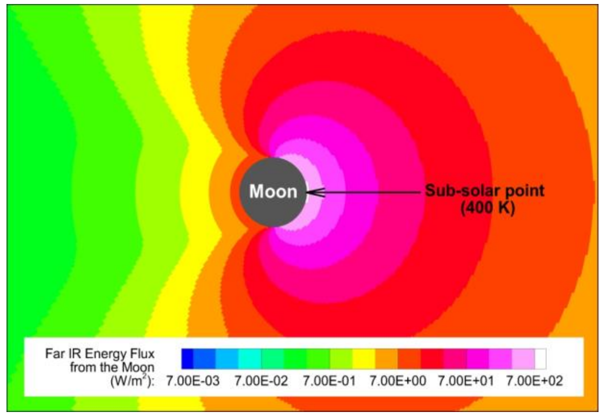

Fig. 2. Estimated far infrared energy flux to space from the lunar surface. For comparison, the solar far infrared energy flux is ~1 W/m^2. Lunar surface temperature varies as $\cos^{1/4}\delta$ (δ = sub-solar zenith angle).

cometary water remains aloft, radiative heat transfer is an important consideration that has a strong influence on the structure of the transient atmosphere.

Conclusions: The transient atmosphere generated by a large-scale release of volatiles on a normally airless body is sufficiently dense that transport processes other than collisionless hopping dominate. Volatiles are thus redistributed differently, particularly in the vicinity of the antipode. In addition to the characteristic structure of the transient atmosphere, we discuss here several physical processes – shielding, photochemistry and radiative heating – that further influence the fate of water delivered by lunar comet impacts.

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