The Transformation of the Lunar Exosphere by a Comet Impact

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Background and Motivation: Several observations suggest that water and other volatiles delivered by past comet impacts may have migrated to permanently shadowed regions near the poles of the Moon and Mercury, where they may still remain cold-trapped¹. In this context, understanding the impact-delivery mechanism is critical to understanding the lunar volatile inventory. The sheer quantity of volatiles delivered by a comet can transform the way in which volatile transport and deposition occur on an otherwise airless body, with implications for the abundance and distribution of volatiles today. Here we use numerical simulations to investigate the nature of volatile transport, loss and deposition after a lunar comet impact.

Method: We adopt a hybrid approach², involving the use of two codes, as illustrated in the schematic below. The **SOVA hydrocode³** is used to model the initial, hydrodynamic flow of molten/vaporized rock and ice. Output from the SOVA code is then used to generate representative water molecules that are tracked using the **Direct Simulation Monte Carlo (DSMC)⁴** method.



Simulated molecules move under variable gravity, interact with each other through collisions and have a temperature-dependent residence time on the lunar surface. Molecules are tracked until escape, photodestruction or cold-trap capture. Macroscopic properties can be determined by sampling molecular properties. The impact-generated atmosphere is treated as optically thick in the ultraviolet (i.e. photodestructive solar radiation is attenuated and may not reach lower layers of the atmosphere), but optically thin in the infrared (i.e. infrared radiation – be it from the Sun, the lunar surface or spontaneous emission by molecules – escapes to space).

Results: I. Structure of the impact-generated atmosphere:



Upon impact (here, at 30 km/s and an angle of 60° from the horizontal), the comet nucleus vaporizes. Initially, the water vapor generated expands rapidly away from the point of impact. The vapor cloud expands to surround the Moon and gravitationally bound vapor falls back to the lunar surface within a nearly spherical 'fallback envelope' (outlined at 6 h after impact), which grows in size with time as vapor begins to fall back from progressively higher altitudes. Re-convergence of vapor antipodal to the point of impact results in a cylindrical shock that channels vapor down to the surface around the

antipode. Vapor falling back to the cold lunar night-side largely remains frozen until sunrise, but vapor falling back to the warm day-side remains aloft, resulting in a low-altitude shock over the day-side hemisphere.

Across the shock, vapor is (A) compressed, (B) slowed and deflected – giving rise to pressure-driven winds that carry water from day-side to night-side and (here, for an impact at the North Pole) from north to south. Vapor is also (C) heated across the shock but, since we assume that the atmosphere is transparent to infrared radiation, radiative cooling lowers the post-shock temperature. The dense, cool vapor below the shock is super-saturated (pressure, P > vapor pressure, P_{vap}) and therefore, condensation could occur in the presence of seed particles (such as dust). This is not currently modeled. Additionally, the assumption that infrared radiation escapes to space without atmospheric reabsorption should be revisited.

II. Non-uniform cold-trapping: Delivery mechanisms that rely on collisionless migration of molecules to the poles should lead to uniform filling of cold traps. However, observations of the lunar poles suggest that water ice, if present, appears to be heterogeneously distributed between cold traps. These differences could be explained in part by local variations in topography and thermal history but certain delivery mechanisms, such as comet impacts, could also distribute volatiles nonuniformly between cold traps. Maps of simulated transient frost cover around the lunar South Pole, shown below, suggest that the collisional nature of the impactgenerated atmosphere can result in a non-uniform redistribution of volatiles (in this case, water). Six modeled cold traps at the South Pole are shown for scale. It should be noted that this particular frost deposition pattern is a consequence of the selected impact location - at the North Pole. It can be seen that the antipodal shock leaves a footprint in terms of non-uniform frost cover where it intercepts the lunar surface. The atmosphere becomes less collisional with time as more water is photodestroyed/deposited, leading to the weakening of the antipodal shock and the smearing of initial non-uniformities.



	Area (km²)	6 hours		72 hours	
Cold trap		Water captured (kg/km²)	Relative magnitude	Water captured (kg/km²)	Relative magnitude
Cabeus Faustini de Gerlache Haworth Shackleton Shoemaker	897 697 314 1295 201 1170	$\begin{array}{c} 4.65 \times 10^5 \\ 6.09 \times 10^5 \\ 8.31 \times 10^5 \\ 5.75 \times 10^5 \\ 2.20 \times 10^6 \\ 6.84 \times 10^5 \end{array}$	1.00 1.31 1.79 1.24 4.73 1.47	$\begin{array}{c} 2.80 \times 10^{6} \\ 2.86 \times 10^{6} \\ 3.85 \times 10^{6} \\ 3.01 \times 10^{6} \\ 6.49 \times 10^{6} \\ 2.39 \times 10^{6} \end{array}$	1.17 1.20 1.61 1.26 <u>2.72</u> 1.00

The table above compares the amounts of water captured by the six modeled cold traps. At 72 h after impact, the contrast in volatile abundance between the different cold traps is reduced compared to 6 h. Longer-term simulations are required to ascertain to what degree initial non-uniformities are preserved as the atmosphere transitions to the collisionless limit (and deposition becomes more uniform).

III. Photochemistry in the impact-generated atmosphere: Our simulations account for the attenuation in intensity of solar ultraviolet radiation as it passes through the absorbing water vapor atmosphere. The calculations show that for several days after impact, the atmosphere is sufficiently dense to shield a significant portion of itself from photodestruction – an effect that is absent in a collisionless exosphere. The gravitational field of the airless body under consideration is doubly important: the more vapor is shielded from photodestruction. This could, however, be offset by a harsher solar environment. Currently, water is the only species modeled i.e. dissociation products and chemical reactions are ignored.

Summary:

- Characteristics of volatile transport and sequestration after a comet impact:
- Until the impact-generated atmosphere becomes collisionless, volatile transport occurs through pressure-driven winds vs. random walk through ballistic hops.
- Atmospheric shock structures could lead to non-uniform cold trap deposition patterns and increased deposition antipodal to the impact location.
- 3. The impact-generated atmosphere may be sufficiently thick that lower layers are shielded from destructive solar radiation.
- Further discussion in Prem et al., 2014 (Icarus).

References: 1. Feldman et al., 2000 (JGR); Spudis et al., 2010 (Geophys. Res. Lett.); Colaprete et al., 2010 (Science); Gladstone et al., 2012 (JGR) and several other observations. 2. Stewart et al., 2010 (Icarus). 3. Shuvalov, 1999 (Shock Waves). 4. Bird, 1994 (Oxf. Univ. Press). <u>Acknowledgements:</u> This work was supported by the NASA LASER program, with generous computational support from the Texas Advanced Computing Center and the Planetary Science Institute.