Cometary Delivery of Lunar Water: The Influence of Impact Parameters

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Introduction Over the last four billion years, ~10^{17} kg of cometary material is estimated to have impacted the Moon (Morgan and Shemansky, 1991). Water ice is thought to be the major constituent of comet nuclei, and although, due to tremendous impact velocities (20-50 km/s), much of the water that comets deliver to the moon may simply escape, analysis of hydrogen isotopes in lunar minerals (Greenwood *et al*., 2011) suggests that some water is retained.

On impact, the comet vaporizes. The velocity, temperature and other characteristics of the vapor plume generated depend on impact parameters such as the angle and velocity of impact, comet density and relative porosity. These impact parameters could in turn determine how much cometary water is retained on the moon, but their precise influence is difficult to determine analytically.

Here, we begin a parametric study of the influence of impact parameters by simulating the impact on the Moon of a comet of pure water ice, 2 km in diameter, travelling at 30 km/s, at impact angles of 45° (Stewart *et al*., 2011) and 60°. The two sets of results are compared and implications for long-term retention of cometary water in lunar cold traps (permanently shadowed craters) are analyzed.

Methodology The immediate physics of the impact are modeled using the SOVA hydrocode, which simulates the phase changes that occur in both the target and the projectile as a result of successive compression and rarefaction waves, and solves for the hydrodynamic flow of molten/vaporized target and projectile material.

The subsequent evolution of the water vapor plume is tracked using a Direct Simulation Monte Carlo (DSMC; Bird, 1994) code designed to model rarefied planetary flows. Unsteady data from the SOVA solution (density, bulk velocity, temperature etc.) are output over a 20 km radius hemispherical shell of cells centered at the point of impact. The SOVA output is then used to 'create' DSMC molecules that 'drift' into the planetary-scale DSMC domain.

DSMC models molecular interactions by moving (under gravitational acceleration) and colliding a representative number of simulated molecules. Molecular properties are then sampled within cells to determine macroscopic characteristics. If, during its motion, a molecule lands at an area on the lunar surface designated as a cold trap (we include six cold traps at the lunar South Pole and one at the North Pole), it sticks to the surface. Molecules in sunlight may undergo photodestruction.

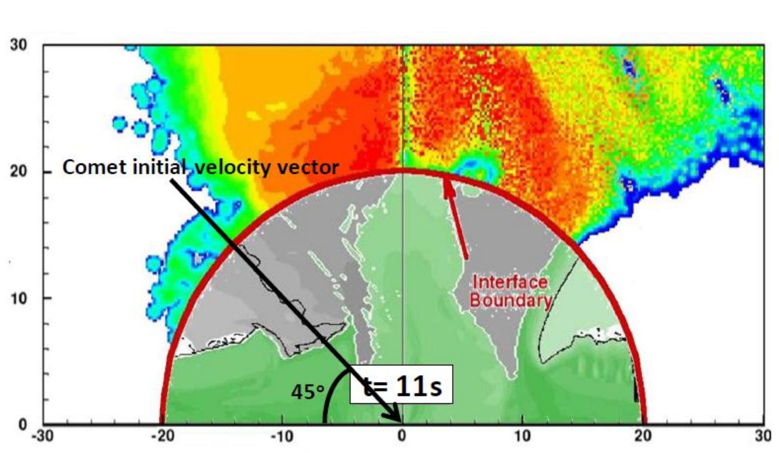

Figure 1 ***Density contours from SOVA and DSMC, 11 s after the 45° impact.*** The green and grey regions within the red semi-circle (the interface between the codes) are SOVA contours for rock (dunite) and water respectively. The DSMC code models only water vapor.

Results The SOVA simulations were run for 21 s (for the 45° impact) and 30 s (for the 60° impact) and the output at intervals of ~ 1 ms was used as input to the DSMC code. Here, we compare the two scenarios in the short term.

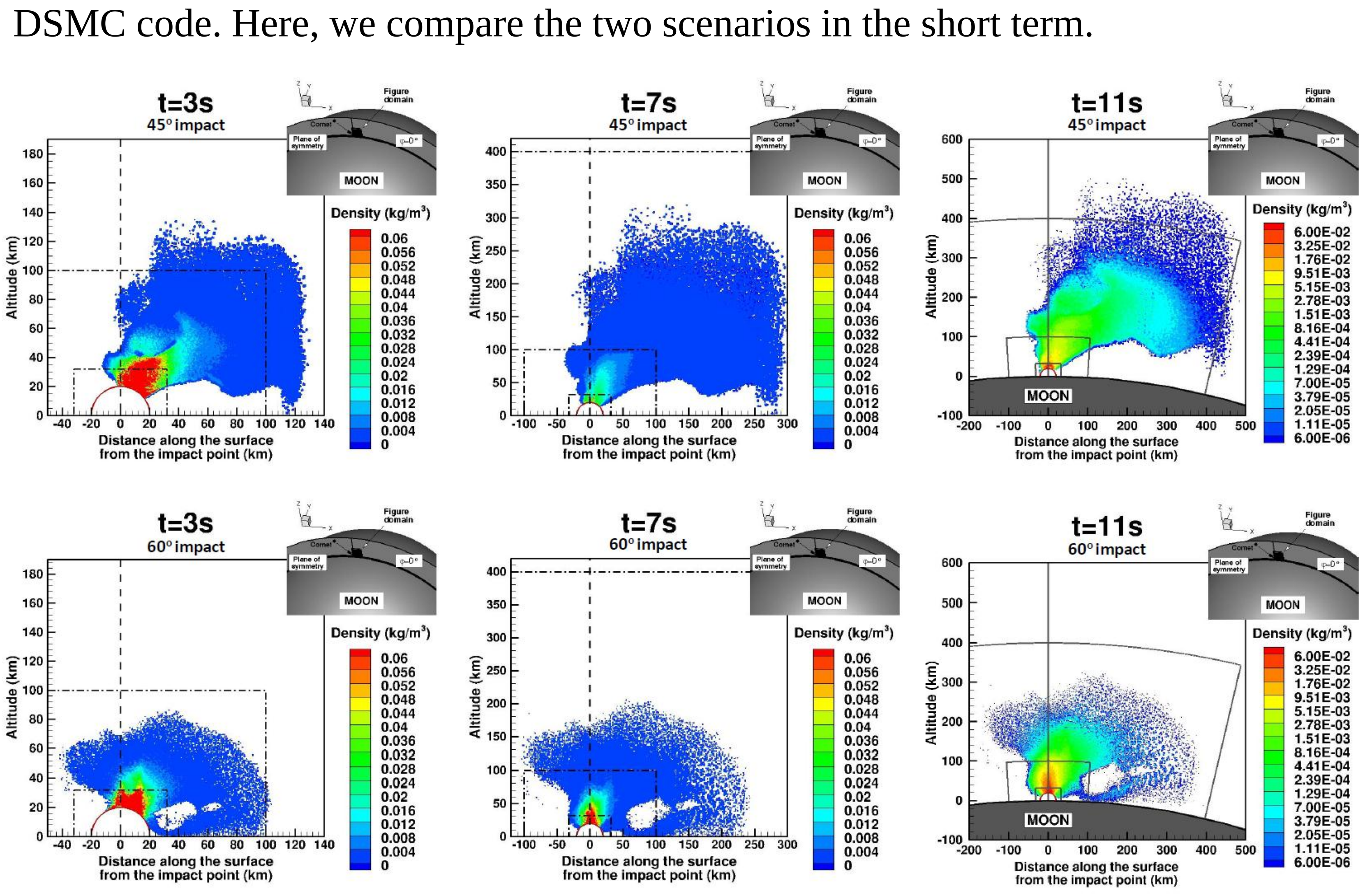

Figure 2 ***Density contours in the plane of impact for the 45° (above) and 60° (below) impacts, 3 s, 7 s and 11 s after impact. Note that the length scales differ, and that the color bar changes from linear to exponential between 7 s and 11 s.***

In both impact cases, the rapid rarefaction of the vapor plume as it expands can be observed. In addition, it can be seen that vertical and downrange velocities of the plume are lower for the 60° impact. In the 60° case, there is also less downrange focusing of vapor. Qualitatively, this agrees with other studies of the fate of a (lower velocity, larger size, dunite) projectile (Pierazzo and Melosh, 2000).

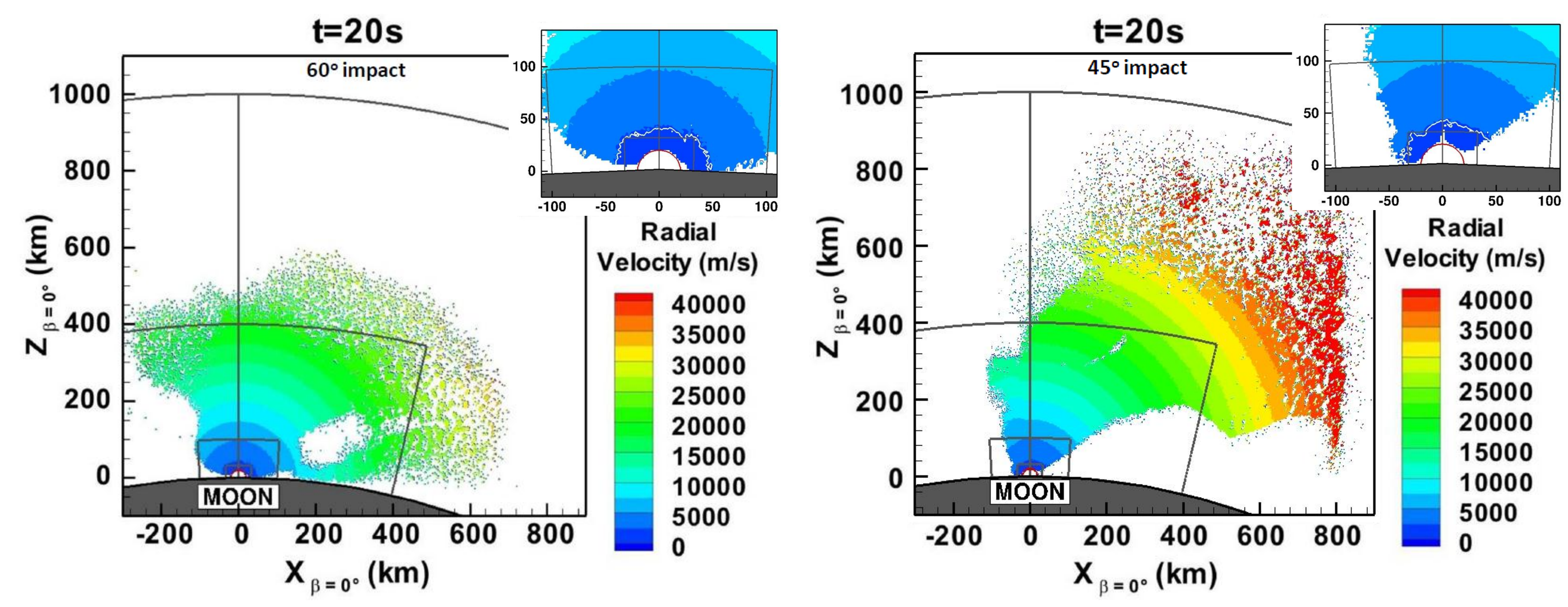

Figure 3 ***Radial velocity contours in the plane of impact for the 60° (left) and 45° (right) impacts, 20 s after impact.*** The 'hole' in the vapor plume in the 60° case indicates regions where target material crossed the SOVA interface. Since we only model water vapor, these regions appear as gaps. Although water vapor is free to move into these empty spaces, lateral motion is very small. The flow is predominantly radially outwards, as indicated by the rings of constant velocity.

Although there is a larger fraction of relatively slow-moving vapor in the 60° plume than in the 45° plume, most of the vapor is still travelling at velocities far greater than lunar escape velocity (~2380 m/s). The white lines in the inset images enclose regions of vapor with velocities below escape velocity, that are thus more likely to be retained in a transient atmosphere.

Vapor may further accelerate due to expansion or decelerate due to collisions, but since there is more vapor traveling below escape velocity in the 60° impact, we can qualitatively predict more long-term retention of water in this case.

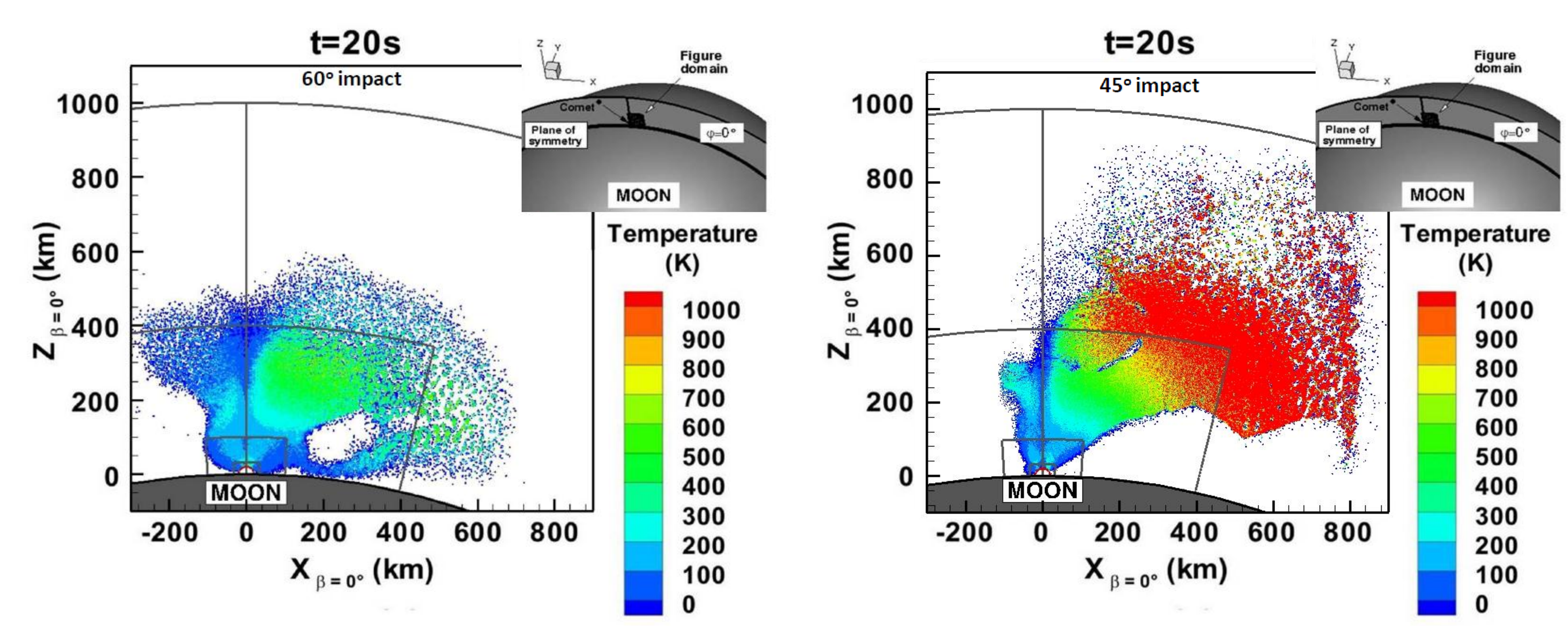

Figure 4 ***Translational temperature contours in the plane of impact for the 60° (left) and 45° (right) impacts, 20 s after impact. Zero temperatures at the rarefied outer fringes of the plumes are due to cells that contain only one simulation molecule.***

It can be seen that the temperature of the 60° plume is significantly lower. An interesting feature in both impacts is the presence of a high temperature region towards the downrange edge of the plume. These regions correspond to material that crossed the SOVA interface with high temperatures and velocities, indicating that the cooling of the vapor plume as it expands is not sufficient to overcome initial high temperatures. This is something that analytical models, which often assume uniform, well-mixed plumes, could not have predicted.

Next Stages At the end of the SOVA simulations, approximately 1% and 10% of the total comet mass has not crossed the SOVA-DSMC interface (for the 45° and 60° impacts respectively). Currently, this water has been assumed to sublimate at an exponentially decaying rate from a circular impact crater, 30 km in radius, centered at the point of impact.

Long term simulations (~ months after impact) of this water, and the water that crossed the SOVA-DSMC interface in under 21 s as a vapor plume, were carried out for the 45° impact (Stewart *et al*., 2011), assuming several different impact locations. It was found that ~0.1% of the comet mass was deposited in cold traps (~1 mm ice over the cold trap areas used). Similar long term simulations are to be carried out for the 60° impact. We intend to use the 45° – 2 km diameter – 30 km/s case as a base case to which the 60° case, and other cases to be run (with a lower impact speed, and lower comet density) can be compared.

Conclusions

- The angle of impact has a significant influence on the shape, velocity and temperature of the vapor plume generated by a comet impact.
- Our simulations indicate that, in the short term, more water is likely to be retained on the Moon for a more vertical impact.
- In the long term, some cometary water (~0.1% of comet mass for the 45° impact simulated) seems likely to be deposited in lunar cold traps.