SIMULATION OF LOW DENSITY ATMOSPHERIC FLOW ON THE MOON FOLLOWING A COMET IMPACT.

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Introduction: The presence of water in cold traps at the lunar poles can be a possible explanation for some of the findings by the Clementine [1] and Lunar Prospector [2] missions. Episodic comet impact events are investigated in this work as a possible source for this water. We examine the flow of expanding gaseous material after a large impact by coupling the Direct Simulation Monte Carlo (DSMC) code to the output of a SOVA hydrocode simulation of an impact event. In the case when the target planet has a tenuous or no atmosphere, the gases following the impact will expand rapidly to become extremely rarefied after a few minutes. In this case the most accurate modeling approach is to treat the gas as a combination of molecules (approach used by the DSMC code) rather than a continuum (approach used by hydrocodes). The DSMC code can therefore follow accurately the entire evolution of the resulting transient atmosphere.

SOVA Simulations: SOVA [3] models multidimensional, multimaterial, large deformation flows. A two-step Eulerian scheme is used to solve for the unsteady flow inside a three-dimensional (3D) domain. The physical changes of the materials are calculated using a tabular version of the ANEOS equations of state [4] and their time evolution is recorded using Lagrangian tracers. A spatial resolution of 20 cells-per-projectile-radius is maintained over a central region around the impact point, followed by progressively lower resolution. In the present simulations, a 2 km diameter water ice sphere hits the surface of the Moon at 30 km/s at a 45° angle.

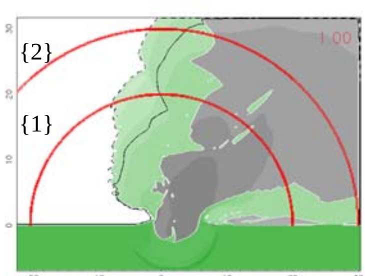
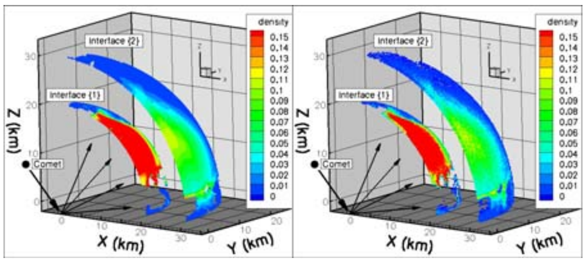


Fig. 1. Density shading from the SOVA hydrocode 1s after the impact. Grey represents the impactor material (water) (darker grey, denser material) and green represents the target material (granite). The red lines respresent the "connection hemispheres" where output data from the SOVA runs are used as input for the DSMC simulations. For this oblique impact, SOVA data were provided at interfaces {1} and {2} so that DSMC simulations using data at {1} could be compared to SOVA results at {2}.

DSMC Simulations: In the DSMC approach the flow of the entire gas is statistically extrapolated from the computed motions and collisions of a relatively small number of representative molecules (O(10^6)) [5]. The present simulation is the first application of the DSMC method in spherical geometry and the first for a full planet atmospheric simulation. An initially two-dimensional (2D) axisymmetric DSMC code [5] has been modified into a 3D parallel code using spherical coordinates. Input data to the present DSMC simulations are the SOVA output data (density, pressure, temperature, etc.) on a "connection hemisphere" above the Moon's surface centered at the impact point. The radius of this hemisphere has been chosen so that the density at this interface is within a range acceptable for both SOVA and DSMC simulations. The density has to be large enough for the continuum flow SOVA runs and low enough to be computationally inexpensive for the DSMC simulations For the present simulations, a reasonable distance appears to be around 20 projectile radii away from impact point, i.e. a radius of 20 km for the connection hemisphere {1}. At this distance, the density at the hemisphere's surface is smaller than 0.8 kg/m^3 which can be handled properly by both codes.

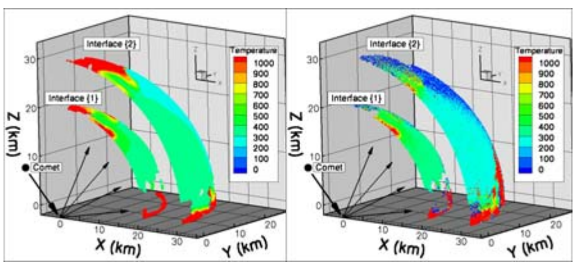
The DSMC code uses an acceptance-rejection method to create molecules at each timestep based on the SOVA data at that time. Once created, the molecules can move and collide according to the DSMC algorithm. We are assuming that flow is hypersonic at the interface, and we only use the water vapor data from SOVA for the simulation of the transient atmosphere with DSMC, neglecting rocky material, which will mostly be in a molten or solid state..

Early Time Results: The interface between the SOVA hydrocode and the DSMC code has been verified by matching density and temperature for the impact seen in Figure 1. The data at the interface {1} is used as input to the DSMC simulation and the DSMC results are then compared at both interfaces with the SOVA results. The DSMC simulation was run on 34 processors with a nonuniform distribution of the domain between the processors for load balancing. The domain is divided in 200x200x126 cells and 15M molecules are simulated. The density contours for the DSMC and SOVA simulations are compared in Figure 2 and the temperature contours are compared in Figure 3. The DSMC and SOVA density contours match well. The temperature contours compare well in the high density areas but not so well in the lower density areas (see top of contours at both interfaces in Figure 3). The noticeable differences are probably due on one end to the intrinsic difficulty of SOVA to simulate the low density regions and on the other end to a potentially insufficient number of representative molecules in those low density regions in the DSMC code.



(a) (b)

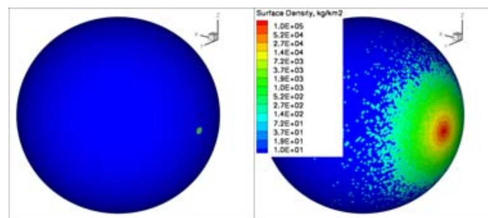
Fig. 2. Density contours at the interfaces {1} and {2}, 1s after the impact: (a) from the SOVA simulation and (b) from the DSMC simulation.



(a) (b)

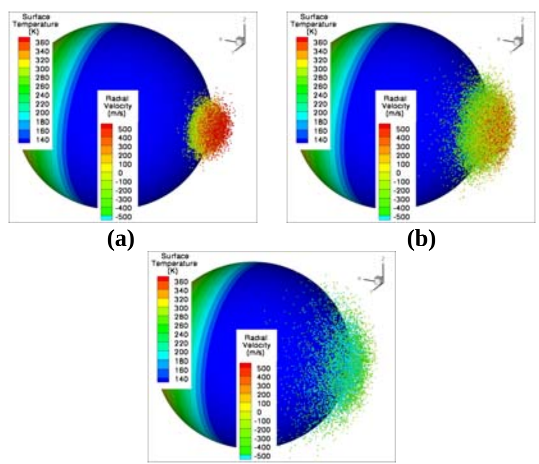
Fig. 3. Temperature contours at the interfaces {1} and {2}, 1s after the impact: (a) from the SOVA simulation and (b) from the DSMC simulation.

Full Planet Results: Figures 1 to 3 show a close-up view of the impact point with a domain size of 30km×30km×30km. We next consider the far field encompassing the entire planet. To show the potential of DSMC to model the evolution of a transient atmosphere, we present DSMC results obtained when the entire Moon is simulated with a ring source of molecules at the surface. *This corresponds to a much later time, when most of the water molecule that did not escape the Moon have been deposited on the Moon's surface.* We use a 30km ring of water molecules at an assumed mud temperature of 300K representing a total mass of $1.5x10^{10}$kg (Figure 4a). The molecules sublimate from this area until the entire assumed deposited mass has been released. After the initial sublimation it is expected that molecules will hop around the Moon until they are destroyed or they reach a cold trap. In this preliminary simulations the physics of the transport process is modeled but the cold traps' distribution is not yet included. Molecules that hit the surface of the Moon will stick to it for a set residence time, which depends on the surface temperature, and while in flight in the sunlit part of the atmosphere molecules can be destroyed due to photodissociation or photoionization. These simulations start with the impact point located on the dark side of the Moon and molecules sublimate for 10 minutes releasing $1.5x10^{10}$kg of water (Figure 4). The sublimating plume of water molecules is observed at various times up to one hour later (Figure 5). At early times molecules have a net upward radial velocity as they are just released from the surface while at later times molecules are falling back to the surface with a net negative radial velocity. One hour after the beginning of the sublimation phase (Figure 4b), most of the molecules have returned to the surface and the will stick to it until the sunrise heats the surface to a temperature large enough for the water molecules to be re-released.



(a) (b)

Fig. 4. (a) Sublimating ring of water molecules on the dark side of the Moon and (b) deposition distribution of the water molecules on the dark side of the Moon one hour after the initial release.



(a) (b)

(c)

Fig. 5. Sublimating plume of water molecules (a) 10, (b) 20 and (c) 30 minutes after the beginning of the release.

References: [1] Shuvalov V. V. (1999) *Shock Waves*, *9*, 381-390. [2] Nozette S. (1996) *Science*, *274*, 1495-1498. [3] Feldman W. C. (1998) *Science*, *281*, 1489-1493. [4] Thompson S.L. & Lauson H.S. (1972) *SC-RR-61 0714*, Sandia Nat. Labs. [5] Zhang J. et al. (2003) *Icarus*, *163*, 182-197.