VOLATILE RETENTION DURING COMETARY IMPACT ON THE MOON AND MARS L. Ong[1], E. Asphaug[1], F. Nimmo[1], D. Korycanksy[1], R. Coker[2], [1]Department of Earth and Planetary Sciences, University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064, long@pmc.ucsc.edu, [2]Los Alamos National Laboratory, Los Alamos, NM 87545

Introduction: The presence of water ice trapped within permanently shaded regions on the Moon was first posited in the early stages of lunar exploration [1] and remains a possibility decades later. The Lunar Prospector Spectroscopy Experiment observed high abundances of hydrogen generally distributed near both lunar poles relative to the hydrogen abundance measured at the equator [2]. Many emplacement mechanisms for the observed hydrogen are hypothesized and include recent impact of a comet onto the lunar surface [3, 4].

Comet impacts have also been suggested as a delivery mechanism for methane recently observed on Mars [5]. Here we investigate the feasibility of volatile delivery to terrestrial planets via comet impacts. We use a novel set of hydrocode calculations to compute volatile retention as a function of impact velocity and atmospheric pressure.

Lunar Impactor Population: The comet population includes both long-period an short-period comets (and the less abundant Halley family); these fluxes are given by Weissman [6, 7] and Shoemaker *et al.* [8]. Zahnle [9] indicates that the total flux of "live comets" is 10 per ~3.7 Ga, much lower than Weissman's reported flux. We shall use both values as end-members. Scaling to the Moon, the cumulative impact rate for both short-period and long-period comets with mass greater than 10^{15} g is taken to be:

$$f_{SP+LP>10^{15}\,gm} = 2.7\times10^{-9}\ /\ yr - 1.1\times10^{-7}\ /\ yr$$

A simple power law describes the comet populations assuming a density of 600 kg/m^3 [e.g. 10, 11]:

$$N(>m) = \left(\frac{m}{1.0\times10^{15}\,gm}\right)^{-0.83}$$

We calculate the cumulative impact rates assuming comets are 50% water by mass. This leads to a total water ice mass flux at the Moon of 6.4x10^4 kg/year to 2.6x10^6 kg/year, where we integrate over comets from 500 m to 100 km in diameter. Little is known concerning the flux of the largest comets and comets smaller than about 1 km in the inner solar system, and changing the limits of integration to include comets as large as 250 km and as small as 100 m changes the mass flux by a factor of 2.

Impact Velocity distribution: The impact velocity distribution is dependent on relative impact frequency and the mean and mode impact velocities for each of Jupiter-family, Halley-family, and Long Period comets [7]. We approximate this distribution by assuming a bimodal sum of two Normal distributions weighted by relative impactor flux:

$$P(v) = 0.58\left(\frac{1}{5\sqrt{2\pi}}\right)e^{\left(-\frac{(v-20)^2}{2(5)^2}\right)} + 0.42\left(\frac{1}{5\sqrt{2\pi}}\right)e^{\left(-\frac{(v-54)^2}{2(5)^2}\right)}$$

Jupiter-family comets impact with a mode velocity of 20 kms^{-1}, while Halley family comets and Long-period comets impact with a mode velocity of 54 kms^{-1}. We assume a sigma of 5 kms^{-1}.

Modeling: We use a new modeling method to calculate the water retention rates from cometary impacts on the Moon and Mars. Previous studies have employed massless Lagrangian tracer particles to follow the trajectory of projectile material, where each particle represents a volume of projectile material. The representation of volumes by tracers introduces errors of up to 10% from geometry alone [12]. We instead directly sum the masses of materials as they flow through the outflow boundaries, summing masses that are faster than escape velocity for each material at each time step. The RAGE hydrocode is particularly suited for this method because multiple materials are handled using separate advection steps for each material in a mixed material cell. For comparison, our own use of tracers for the mass flux indicates that tracers can significantly overestimate the amount of volatiles retained.

RAGE Hydrocode. We used the continuous adaptive mesh Eulerian hydrocode RAGE, which was jointly developed by Los Alamos National Laboratory and Science Applications International. RAGE has been extensively validated against diverse analytic test cases and detailed experiments [13, 14].

Equations of State The accuracy of a model for the fate of the water in a cometary collision depends sensitively upon the equation of state. The Pactech/SAIC water EOS incorporates six ice phases, the liquid phase, and the gas phase. Pactech/SIAC water EOS phase boundaries correspond very well to empirical phase boundary data, including all triple points [15]. We use the SESAME equation of state for basalt to simulate the Martian and Lunar surfaces.

Model Parameters We model 1 km. diameter ice spheres impacting into basalt at vertical incidence. Both the projectile and target are modeled at full density. In the lunar case, for numerical reasons our simulations include a tenuous 1 dyne/cm^2 background atmosphere (SESAME solar wind mix). We test the velocity dependence of volatile retention at impact velocities of: 15, 30, 45, and 60 kms^{-1}. For the Martian case we apply varying atmospheric pressures to a 45 kms^{-1} impact. We model the atmosphere using the SESAME CO_2 tables.

Results: *Velocity Dependence* The fractional impactor mass retained drops precipitously from 0.2 for 15 kms^{-1} impacts to $<10^{-5}$ for high velocity impacts (Fig. 1). Mass retained from 60 kms^{-1} impacts is significantly lower than that predicted by the analytical model of a hemispherically expanding vapor plume [16, 17]. Future work includes resolution convergence and boundary convergence tests, as well as models with velocities between 45 kms^{-1} and 60 kms^{-1}, to explore this deviation.

Atmospheric Dependence Initial results show that as expected, the fractional impactor mass retained increases with increasing atmospheric pressures. However, for pressures below 0.01 mbar the variation in mass retained is negligible.

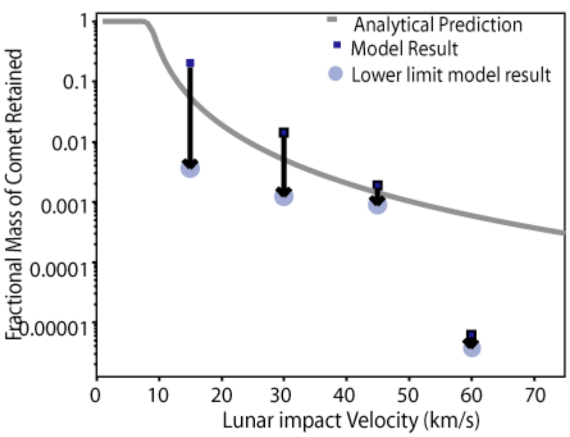

Fig. 1 Comparison of mass fraction of volatiles gravitationally retained on the Moon from hydrocode models and an analytically expanding vapor plume [16, 17], for vertical impacts of solid ice spheres into basalt with lunar gravity. Squares indicate mass retained summed through outflow regions; circles indicate lower limit of fractional mass retained assuming all impactor material remaining in the grid escapes. Since most of the impactor material remaining in the grid is likely moving slowly, actual uncertainty in our results is smaller than the arrows indicate.

Discussion: We use our model results to determine the fraction of impactor retained as a function of velocity, and apply this to the probability of impact at a given velocity to determine the total fraction of water retained for impacts $v_{esc} < v_{impact} <$ 75 kms^{-1}. We find that 7.8% of water is retained over this range of impact velocities. This value is sensitive to the peak of the velocity distribution at ~20 kms^{-1}, where ~6% of cometary volatiles are retained. We multiply the cumulative fraction of water retained over the water mass flux derived from the impactor population, and determine that $9.9x10^{9}$ to $4.0x10^{11}$ metric tons of water are delivered to the Moon over 2 Ga. Survival rates of water molecules during migration to the lunar poles and other post-impact processes range from 2.4% [18] to 50% [19]. Additionally, Crider and Vondrak [20] find an average retention efficiency of 5.6% once water molecules have reached the lunar poles. Assuming these values are correct, a total of $1.3x10^{7}$ to $1.1x10^{10}$ metric tons of water ice might be present at the Lunar Poles today. The mass of ice estimated to be at the lunar poles by Feldman *et al.* [2] is $6x10^{9}$ metric tons, and is encompassed by our range. Better constraints on the cometary impact flux are necessary to refine our estimates.

For impacts into planets with substantial atmospheres, we expect our models to determine at which atmospheric pressure, if any, there is a significant increase in the fractional mass of retained volatiles.

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