WATER DELIVERED TO THE MOON BY COMET IMPACTS. L. Ong[1], E. Asphaug[1], and C. Plesko[1], [1]Department of Earth Sciences, University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064, long@pmc.ucsc.edu

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. Arecibo radio observations of the monostatic circular polarization ratio [2] and data from the Clementine Bistatic Radar Experiment [3] suggested the presence of ice in the basins of permanently shaded craters near the lunar South Pole. Interpretations for both datasets varied, however, and subsequent analyses of the data do not illustrate conclusively the presence of water ice.

More recently, 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. The hydrogen observed is interpreted to lie in within both sunny and permanently shaded circumpolar craters [4], so the Lunar Prospector results neither bolster nor undermine the water ice hypothesis. Many emplacement mechanisms for the observed hydrogen are hypothesized, including: fluid inclusions from impacting stony meteorites [5], retention of solar hydrogen released in solar flares [6], adsorption of water [7], and recent impact of a comet onto the lunar surface [8, 9].

Comet impacts: We investigate the feasibility of water ice delivery via comet impacts. Considerations for the likelihood of cometary impacts producing polar hydrogen abundances include the probability of cometary impact and water mass flux, the effect of obliquity of the impact on fragmentation and vaporization of the impactor, and the migration of water vapor to the cold traps in the lunar polar regions. We will report on the fraction of water delivered to the lunar surface that remains bound, during a suite of comet impact simulations, and provide information on the initial mass-velocity distribution of impact-delivered water.

Impactor Populations. Impactor populations for both long-period and short-period comets are based on the inner solar-system values given by McKinnon et al. (1997) and Korycansky and Zahnle (2005) [10, 11]. The cumulative impact rate for both short-period and long-period comets with mass greater than 10^{15} g is taken to be:

$$f_{SP+LP>10^{15}\,gm} = 9.3\times10^{-7}\ /\ yr$$

A simple power law describes the comet populations:

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

We assume the comet density measured from Comet 9P/Tempel-1 during the Deep Impact mission, $\rho = 600\,kg\,/\,m^3$ [12], which is consistent with the density derived for the comet Shoemaker-Levy 9 [13]. We calculate the cumulative impact rates for objects ranging in diameter from 1 m to 100 km (Fig. 1). This leads to a total water ice mass flux at the moon of $4.52\text{x}10^7$ kg/year. However, very little is known concerning the true flux of comets smaller than about 1 km in the inner solar system, so this population is probably overestimated by this simple power law.

Oblique Impacts. Experiments and hydrocode modeling have both shown that obliquity plays an important role in the state and velocity of the projectile after the impact by altering the degree of fragmentation and vaporization of the impactor. Laboratory experiments show decreasing impact angle can cause projectile fragments to ricochet off the target leaving the projectile partially intact [14], and these results have been reproduced in hydrocode modeling [15]. Additionally, impact angle alters the shape and direction of the expanding vapor plume and could affect the timescales of vapor migration to the poles.

Migration of Water Vapor. Watson et al. (1961) first posited a theory for volatile movement on the surface, predicting a small percentage of water vapor near the lunar surface will migrate to cold traps near the poles [1]. Recent simulations have shown up to 50% of water placed on the surface of the moon will migrate to the lunar poles [16]; however, competing analysis concludes no water vapor migrates to cold traps near the polar regions, regardless of emplacement mechanism or geographic location [17]. While the scope of this project does not include analysis of global vapor movement, we hope to apply our results to a vapor migration model in the future.

Modeling: Here we present a novel set of calculations for the fate of cometary water impacting the Moon. We vary impactor diameter, velocity, and impact angle to test water retention rates for cometary delivery of water ice to the Moon.

We use the continuous adaptive mesh Eulerian hydrocode RAGE, which was jointly developed by Los Alamos National Laboratory and Science

Applications International (LANL/SAIC). We model impacts of water-ice spheres with diameter ranging from 10 m to 10 km. Velocities vary from 2 km/s to 3 km/s, and impact angles include 15, 30, 45, and 90 degrees (Table 1).

Table 1. Suite of calculations in progress. While in principle the results should be scale0invariant over comet diameter, in practice the larger comets impact a different substrate than the smaller comets, which encounter upper regolith.

Comet diameter	10 m	100 m	1 km	10 km	
Impact velocity	2 km/s	5 km/s	10 km/s	30 km/s	
Impact angle	15°	30°	45°	60°	90°

Equations of State. For the upper regolith layer, we use the SESAME equation of state for Nevada Alluvium to simulate the shallow lunar regolith [18]. For the deeper substrate we transition to SESAME basalt. Thus, larger impactors excavate into a different and denser material than the smaller impactors, potentially affecting the fate of the delivered water.

Modeling the Comet. The accuracy of a model for the fate of the water in a cometary collision depends sensitively upon the equation of state. For our calculations we use the Pactech/SAIC equation of state for water to simulate the comet impactors. The Pactech/SAIC water EOS incorporates six ice phases, the liquid phase, and the gas phase. Pactech/SAIC water EOS phase boundaries correspond very well to empirical phase boundary data, including all triple points and a Maxwell construction for the vapor dome [19].

Results: Initial simulations of vertical impacts at near-escape velocity produce cold, slowly moving water vapor plumes (Fig. 1). Larger impacts are expected to produce higher ejecta and vapor plume velocities, ejected some percentage of material away from the Moon at escape velocity or higher. We will determine relationships between percentage of impactor material trapped within the gravity of the Moon, impactor velocity and mass, and impact angle, and evaluate the likelihood of cometary impacts for the emplacement of water ice on the Moon.

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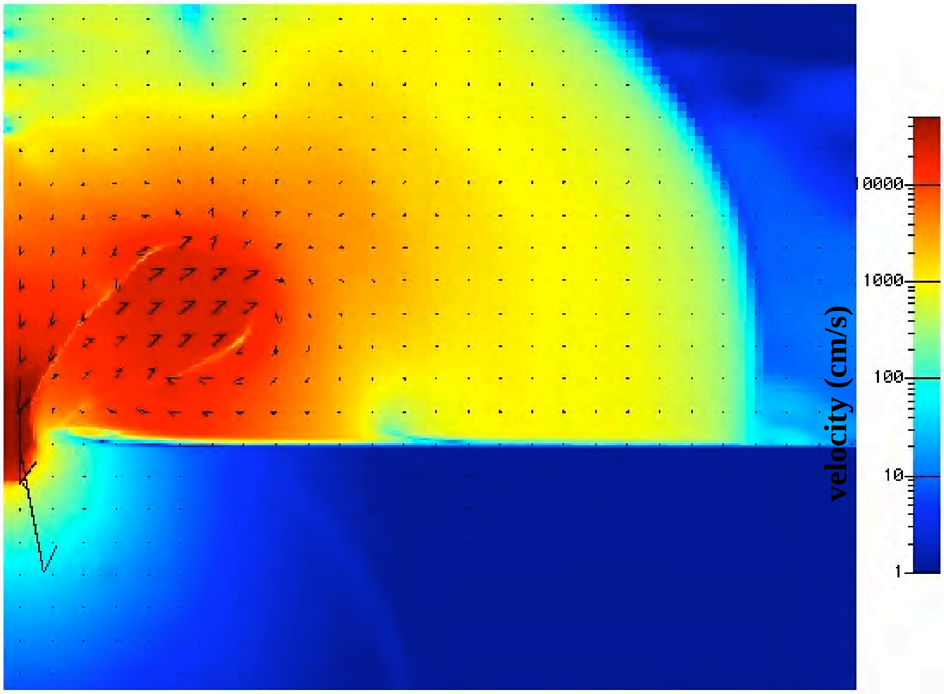

Fig. 1: Velocity plot of target and projectile material 0.1 s after vertical impact of a 100 m diameter comet (ice sphere) impacting the lunar surface at 2.0 km/s (the slowest of the range of velocities in Table 1), at vertical incidence. The vapor plume velocities remain below the escape velocity, trapping all vaporized water near the lunar surface. While the code can be run in 3D, the simulations are time consuming, so oblique incidence collisions will be performed at first in planar symmetry.