VOLATILE RETENTION AND EROSION BY IMPACTS ON MARS

L. Ong[1] and E. Asphaug[1], [1]Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721 long@lpl.arizona.edu, [2]Department of Earth and Planetary Sciences, University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064

Introduction: The recent increase in the number of missions to Mars has produced a torrent of new data that strongly suggest the abundant flow of liquid water sometime in Mars's past. The features, which include round concretions of hematite imaged at Meridiani Planum by the rover Opportunity [1], spectroscopic evidence of hydrated minerals and evaporites [2], and large outflow channels imaged by numerous satellites at various resolutions have been dated to older than 3.5 Ga [3].

Liquid water is unstable at current martian surface temperatures and pressures. Although water can flow in unstable conditions, it is unlikely than an unstable source of liquid water would contain as much volume and flow over long enough time scales to produce the number and geographic extent of outflow features observed today. This liquid water flow hypothesis therefore requires a warmer and denser atmosphere to approach the temperature and pressure conditions necessary for liquid water to be stable.

Here we investigate the question of martian atmospheric evolution through water mass delivery and atmospheric erosion by cometary and asteroidal impacts on Mars. We simulate these competing processes using a new technique to track volatile masses moving faster than escape velocity.

Modeling: We use a new modeling method to calculate the water retention rates from cometary impacts on 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 [4]. To avoid these errors, we directly sum masses that are faster than escape velocity for each material at each time step as they flow through the outflow boundaries. 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. Our own use of tracers for the mass flux indicates that tracers can significantly overestimate the amount of volatiles retained.

Model Parameters We ran a set of initial simulations of impacts of 1-km diameter comets at 45 km s^{-1} for martian atmospheric pressures of 10^{-3} mbar, 0.1 mbar, 1 mbar, 3 mbar, 30 mbar, and 150 mbar to test pressure dependence of volatile retention and atmospheric erosion. We model the projectile as a solid ice sphere at full density and zero strength.

The models included a constant gravitational acceleration of 3.72 m s^{-2} pointed down. Prior to each simulation, the target and background atmosphere were allowed to reach hydrostatic equilibrium. We model the atmosphere using the SESAME CO_2 tables.

Volatile retention: The fractional mass of impactor retained increases with increasing atmospheric pressure in our initial simulations of 1 km-diameter bolides impacting Mars at 45 km s^{-1} (fig. 1). The full impactor mass is retained in the 150 mbar atmosphere impact at 45 km s^{-1}. For impacts at lower velocities we expect a similarly shaped retention curve, but with an offset to lower pressures such that the full mass of the comet is retained at pressures below 150 mbar. The inverse is also expected for impacts at higher velocities.

Very little atmospheric pressure is needed to retain a large fraction of the impactor; 70-80% of the impactor mass is retained at current martian atmospheric pressure (between 6 and 10 mbar) at the relatively high impact velocity of 45 km s^{-1}. Depending on the atmophile composition of the impactor, large quantities of foreign vapor (e.g. CO_2) could be introduced into and remain in the atmosphere. If this is true, significant masses of atmosphere also must be accelerated beyond escape velocity for net atmospheric erosion to take place.

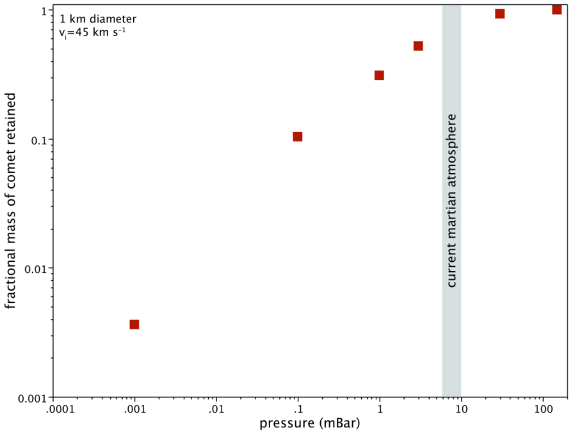

Fig. 1: Volatile retention from an impacting comet as a function of atmospheric pressure for vertical impacts on Mars at 45 km s^{-1}. The fractional mass of comet retained increases sharply with increasing atmospheric pressure. The full impactor mass is retained for targets with 150 mbar atmospheres. At current martian atmospheric pressures (6-10 mbar),

70 to 80% of the impactor mass is retained. Slower impacts, under investigation, are expected to contribute even more mass to the planet.

Atmospheric erosion and the Martian "Sweet Spot": The dependence of atmospheric erosion on pressure on Mars produces a most interesting result. Figure 2 shows the mass of atmosphere lost normalized against the impactor mass as a function of atmospheric pressure for 1-km diameter projectiles impacting at 45 km s^{-1}. At very low pressures, the atmosphere is not very massive and so atmospheric removal, however efficient, does not remove much total mass. As atmospheric pressure increases, the mass of atmosphere eroded increases because of the increase in atmospheric mass available for erosion.

At 1 mbar atmospheric pressure, however, the mass of atmosphere eroded peaks at approximately 6% of the impactor mass. At pressures above 1 mbar, the pressure of the atmosphere becomes comparable to the force provided by the expanding plume, and the plume accelerates a smaller mass of atmosphere to escape velocity. Finally, at 150 mbar the full atmosphere survives the impact with no mass eroded.

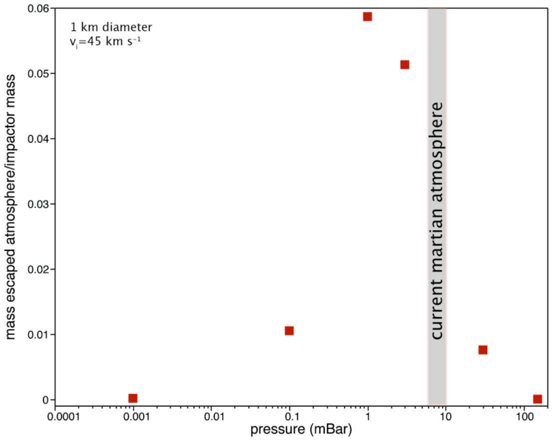

Fig. 2: Atmospheric erosion as a function of atmospheric pressure on Mars. For low-pressure atmospheres, little atmospheric mass is ejected because the atmosphere is low-mass. The mass of atmosphere eroded peaks at atmospheric pressures of 1 mbar with 6% of the impactor mass eroded from the atmosphere. At pressures higher than this, the atmosphere begins to significantly reduce the momentum of the plume and smaller masses of atmospheres are eroded. For these impact conditions, there is a peak of atmospheric loss not far from the present martian atmosphere.

We can now compare the mass of volatiles delivered to Mars and the atmospheric erosion caused by impacts of comets and asteroids. If we assume a water content of 50% for comets and 10% for asteroids by mass (and otherwise assume that ejecta behave as per the pure water-ice comets in our simulations), we can examine the mass balance for volatiles in the martian atmosphere. Comets add much more water than they erode atmosphere, but asteroids can deliver and erode equal masses of atmophiles for impacts into atmospheric pressures greater than 1 mbar. The CO_2 to H_2O ratio in comets is estimated to be 1:100 [5]. If we adopt this ratio, comets could erode up to 22 times more CO_2 than they deliver.

Conclusions and future work: The efficiency of atmospheric erosion is the result of the competing effects of atmospheric mass available for erosion and the pressure that this mass exerts on the expanding vapor plume. Assuming all delivered ices (from comets and asteroids) condense into solids on the martian surface, peak erosion occurs at 1 mbar pressure for these impact conditions. For 1-km diameter comets, the contributed impactor mass is much greater than the mass of atmosphere eroded. For larger impacts or if CO_2 vapor remains in the atmosphere, there might exist an equilibrium atmospheric pressure above which more atmosphere is eroded than volatiles deposited, and below which the opposite is true. If this is the case, Mars may currently occupy a "sweet spot" in which the competing effects of erosion and volatile injection always push the atmospheric pressure towards this equilibrium.

Small impactors are less efficient at impact erosion of atmospheres but impact at higher frequency. We have shown that there is a maximum atmospheric pressure at which an impactor of a given size can produce a vapor plume energetic enough to result in atmospheric erosion. At pressures greater than this, the high fluxes of small impactors produce no atmospheric erosion. Melosh and Vickery [6] find that the largest impactors reduced the martian atmosphere to its current state from an atmosphere with order ~1 bar. It is unlikely that smaller impacts, although more numerous, could erode substantial atmospheres.

Ongoing work includes an investigation of atmospheric erosion that integrates results from various studies to determine the total mass of atmosphere lost with time, for a populations of projectiles of cometary and asteroidal composition.

References: [1]Squyres, S. *et al.* (2004) *Science, 306,* 1709-1714. [2]Bibring, J-P. *et al.* (2005) *Science, 307, 1576-1581.* [3]Carr, M. (1996) *Water on Mars*, Oxford University Press. [4]Pierazzo E. and Melosh H. J. (2000) *Meteoritics and Planetary Science, 35,* 117-130. [5]Encrenaz, T. (1987) *Royal Society Philosophical Trans., 323,* 397-404. [6]Melosh, H.J. and Vickery, A. (1989) *Nature, 338,* 487-489.