NUMERICAL MODELING OF IMPACT EROSION OF ATMOSPHERES: PRELIMINARY RESULTS; A. M. Vickery, Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721

It is clear from the great diversity of atmospheres among the terrestrial planets that their formation and evolution must have depended on a balance among a number of different processes. One of these processes is atmospheric erosion by impacts, which may have been particularly effective on Mars [1]. The reason is that geomorphic evidence on Mars suggests that this planet had, early in its history, a dense enough atmosphere to sustain active precipitation over geologically significant periods of time [2]. Analytic calculations indicate that neither the projectile entering the atmosphere nor the main crater ejecta can cause the loss of significant amounts of atmosphere [3,4]. The vapor plume that is formed, however, expands rapidly as its internal energy is converted into kinetic energy, and may blow off the overlying atmosphere. A model of this part of the impact/atmosphere interaction predicts Mars could have lost a substantial early atmosphere by impact erosion alone [5]. Although our more detailed calculations, which took into account the anisotropy of the atmosphere with respect to zenith angle, show that the process isn’t quite as effective, they still indicate the probability of substantial atmospheric loss from Mars[6]. In this abstract, I discuss the first results from 2-D hydrocode runs. These include two runs which make most of the same simplifying approximations as the analytic models, in order to compare the analytic and numerical results directly, and one run (as yet incomplete) that models the full impact.

The calculations described below use the 2-D hydrocode CSQ with the ANEOS equation of state program. I have started a calculation that follows the impactor as it traverses the atmosphere and then impacts the solid planet. The projectile and target are composed of dunite, and the 1 km diameter projectile approaches the planet at 15 km/s. The atmosphere in this calculation, and in the simpler ones discussed below, is composed of pure CO₂, which is modeled as a perfect gas. The atmosphere is isothermal, with a temperature of 298 K and a surface pressure of 1 bar. The gravitational acceleration is 3.72 m/s², that of Mars. This calculation is extremely difficult to keep stable, requiring small time steps and frequent regridding. After 2 months of working on the problem, the calculation has been carried out to a simulated time of 2 seconds. At this time, the shock wave generated by the passage of the impactor through the atmosphere is expanding outward more-or-less cylindrically, and the shock wave in the target is expanding approximately hemispherically (See figure 1). A crater is beginning to form, and some ejecta is being thrown out, but the calculation has not yet proceeded to the point of following the expansion of the expected vapor plume.

As it became apparent that doing the full-up calculation would take a long time, I decided to start a series of much simplified calculations. The plan is to run models of increasing complexity and verisimilitude, and thereby understand the what factors are important for impact erosion. The first such runs model the expansion of a hemisphere of highly shocked dunite into an exponential atmosphere that overlies a rigid substrate -- essentially the approximation made in the analytic studies. It is assumed that the projectile and an equal mass of target are shocked to the highest pressures given by the planar impact approximation. The initial temperature, pressure, and density of the shocked material are determined from the Hugoniot generated by ANEOS. This material is assumed to start as a hemisphere at rest, and is allowed to expand into the overlying atmosphere, described above. If this material were expanding into a vacuum, theory suggests that it should achieve a mean velocity of 7.5 km/s, with a maximum velocity at the leading edge 2 - 3 times as great.

The first set of results from the simplified problem are for the impact of a 1-km diameter projectile, whose mass is much less than that for catastrophic atmospheric blow-off, as indicated by the analytic models. The evolution of the plume was followed for roughly 18 seconds of problem time, as it expands to nearly 45 km (3 scale heights). The striking thing about these results is that the plume is subject to a Rayleigh-Taylor type instability and begins to break up and mix with the atmosphere at very early stages (figure 2). The velocity in some
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atmosphere; it is clear that this material does not have sufficient momentum to approach the theoretical limiting velocity or to maintain velocities greater than escape velocity. The second such run increased the mass of the vapor plume by a factor of 100, although it is still much less than required for catastrophic blowoff, with all other parameters the same. This calculation followed the expansion for ~ 7 seconds, with the shock front reaching upward to about 50 km and to about 40 km along the "planetary surface". This quasi-elliptical shape is an expected consequence of the density gradient in the atmosphere, which is largest in magnitude directly upward. As for the smaller plume, Rayleigh-Taylor instabilities develop, but are not as pronounced. The time-averaged velocity of the leading edge of the plume is ~ 7.5 km/s in the upward direction and ~ 6 km/s in the horizontal direction. Thus one predicts the loss of some atmosphere in this case, even though the impactor mass is much less than the threshold for catastrophic blow-off.


Figure 1. Full impact calculation of a 1-km diameter dunite projectile through a 1-bar CO2 atmosphere on Mars at 15 km/s. Time = 1.75 s.

Figure 2. Material interface plot showing the originally hemispherical plume breaking up and mixing with the atmosphere. Time = 8.54 s.