ATMOSPHERIC EROSION BY PLANETARY IMPACTS. D. G. Korycansky, *CODEP, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064* , D. C. Catling, *Department of Earth and Space Sciences, University of Washington*, K. J. Zahnle , *Planetary Systems Branch, NASA Ames Research Center*.

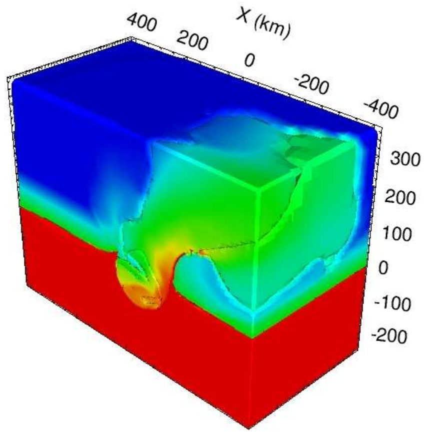

Figure 1: Sample timestep of a local-scale impact modeled with the CTH hydrocode. The figure shows density on a logarithmic scale ($10^{-6} < \rho < 1$ gm cm^{-3}) at $t = 60$ s after the impact of a $d = 36.8$ km object at 20 km s^{-1} ($4 \times v_{esc}$) into the "Mars" target.

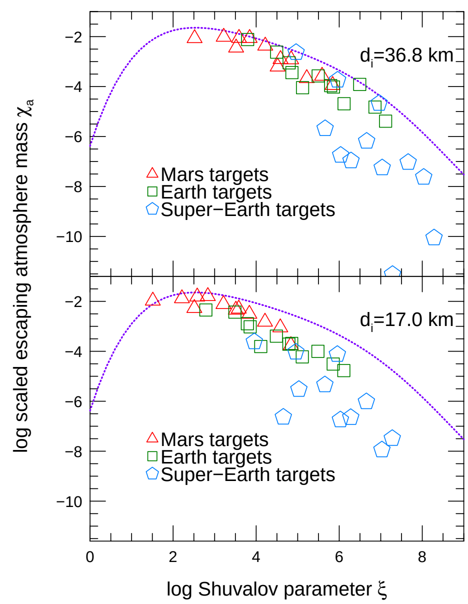

Figure 2: Scaled escaping mass χ_a vs. Shuvalov number ξ for our simulations. Top: Simulations carried out with impactor diameter 36.8 km. Bottom: simulations with impactor diameter 17.0 km.

Hydrodynamic modeling

We present results from numerical modeling of impact erosion of planetary atmospheres using the CTH hydrocode. The calculations discussed here are "local": the curvature of the planet and the radial dependence of the gravitational field are neglected. The computational domain is a cartesian box: the calculations are three-dimensional.

Physical parameters of the simulations include the target-planet properties: three planetary environments are used. Parameters include the gravitational field (vertical gravity g) and the escape velocity that characterize the target. Additionally the surface pressure of the atmosphere and its scale height are set, the latter determined by the atmospheric composition and temperature. This in turn sets the altitude of the exobase, above which material is assumed to move ballistically. The parameters of the impactor are its diameter and velocity; the impactor angle is set to $\theta = 45^\circ$ from the vertical.

We are carrying out the local-scale simulations using the CTH hydrocode from Sandia National Laboratory [1]. CTH is a highly advanced code widely used in the planetary science community. It utilizes adaptive mesh refinement to concentrate computational resources at locations of physical interest in the simulation, such as shock fronts and material interfaces. In addition, it makes use of material strength models and advanced tabular equations of tabular such as ANEOS and the SESAME library from Los Alamos National Laboratory.

We consider impacts into three targets: Mars-like ($g = 370$ cm s^{-2}, $v_{esc} = 5.0$ km s^{-1}), Earth-like ($g = 980$ cm s^{-2}, $v_{esc} = 11.0$ km s^{-1}), and a "Super-Earth" ($g = 2411$ cm s^{-2}, $v_{esc} = 23.5$ km s^{-1}) that matches conditions for an exoplanet of $8M_\oplus$. The surface pressures are $P_{surf} = 1$, 10, and 100 bar. For these first set of calculations we also assume an isothermal CO_2 atmosphere at 300K, leading to exobase altitudes $H_x \sim 400$, 150, and 60 km for the "Mars", "Earth", and "Super-Earth" cases, respectively. Impactor diameters are $d_i = 4.6$, 17, and 36.8 km, and impact velocities are parameterized in terms of the escape velocity: $v_i/v_{esc} = 2$, 4, 6, and 8. Computation domain sizes are based on the maximum of either the transient crater diameter from the impact or the exobase altitude. Likewise the simulation runtimes are based on the maximum crater formation time or the time for impact ejecta moving at v_{esc} to reach the exobase altitude. Both the impact and the target have made of basalt; a simple material model ("geo") in CTH is applied, with a nominal yield strength of 10^9 cm^2 s^{-2}.

Post-impact analysis yields fluxes of material moving at escape speed or faster through the boundaries (chiefly the upper boundary at $z = H_x$); we integrate the flux to get the total amount of escaping material. Although we track three kinds of material (impactor, target surface, atmosphere), here we report only on the last (escaping atmosphere).

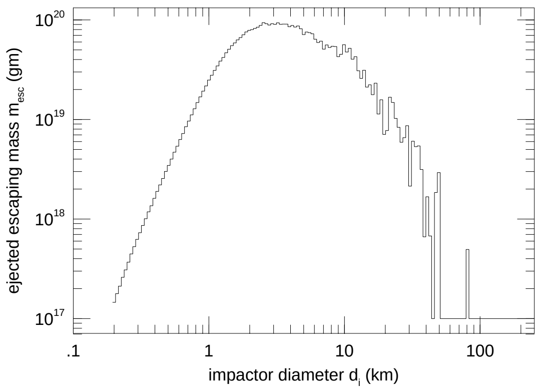

Figure 3: Realization of a Monte Carlo simulation of impact erosion for a Mars-type planet with an atmosphere with $P_{surf} = 10^6$ dyne cm^{-2}, T=300 K. Shown is the amount of escaping mass m_{esc} as a function of impactor diameter d_i.

Simulation Results

We have carried out and analyzed $\sim$ 70 3D calculations so far. A sample timestep from one of the calculations is shown in Fig. 1. The figure shows the density on a logarithmic scale (10^{-6}<ρ<1 gm cm^{-3}) at t=60 s after the impact of a d_i=36.8 km object at 20 km s^{-1} (4$\times v_{esc}$) into the “Mars” target.

Shuvalov scaling

Shuvalov[2] has carried out an extensive set of impact simulations for objects into Mars- and Earth-like targets. He plotted his results in terms of parameters ξ and χ_a, defined in terms of simulation parameters and escaping atmosphere mass: $\xi = (d_i^3 \rho_i / H^3 \rho_0)[\rho_i/(\rho_i+\rho_t)][(v_i^2 - v_{esc}^2)/v_{esc}^2]$, $\chi_a = (m_{esc}/m_i)[v_{esc}^2/(v_i^2 - v_{esc})^2]$ The impactor diameter is d_i, velocity v_i, density ρ_i and mass is m_i; the atmosphere is characterized by surface density ρ_0 and scale height H; the planet escape velocity is v_{esc} and ground (“target”) density ρ_t.

Shuvalov found that his results (χ_a vs ξ) could be well-fit by an empirical fifth-order polynomial in ξ. In Fig. 2 we plot our results in terms of the same variables. For comparison the Shuvalov fit is shown as a dashed curve.

The Shuvalov curve forms an upper envelope to our results. This suggests that our simulations support the use of Shuvalov’s formulation, but that various possible potential problems in our calculations may cause the amount of escaping mass we find to fall short of the Shuvalov curve. For instance, numerical resolution of the calculations may be an issue. It will be noticed that our “Super-Earth” calculations fall farthest below the Shuvalov curve. For these simulations the assumed surface temperature of 300 K generates an atmospheric profile with a scale height of $\sim$ 2 km, which is comparable to the 2–3 km resolution of our calculations. In turn this may reduce the reliability of our results. An easy test of this question will be to carry out calculations with hotter (and thus taller) atmospheres, which will be better resolved in the simulations. Calculations with T=1500 K surface temperature are presently underway.

Monte Carlo simulations of impact erosion

Assuming that the Shuvalov scaling and parameterization is a good description of impact erosion, we can then use these results to model the effects on planetary atmospheres of a population of impactors. The survival of atmospheres for wide variety of planetary environments can thus be tested. We have constructed a Monte Carlo simulation algorithm in which a planet (characterized by mass, radius, and orbital velocity) with a planetary atmosphere (characterized by surface temperature, molecular weight, and surface pressure), is subjected to bombardment from an impactor population (characterized by differential diameter number distribution and velocity at infinity). An impactor with diameter d_i and velocoty v_i is selected from suitable distributions (which include the effects of planetary orbital and escape velocity). Given the atmospheric characteristics (following from the parameters listed above), the Shuvalov parameter ξ is calculated, with χ_a following from Shuvalov’s empirical fit. This results in the mass of escaping atmosphere $m_{esc} = m_i \chi_a$. The escaping ejected mass is subtracted (and ρ_0 accordingly adjusted) until the remaining atmospheric mass falls below a set value such as $0.001\times$ the initial mass. Quantities of interest include the distribution of m_{esc} as a function of impactor diameter d_i (indicating the sizes of the “most effective” impactors) and the total amount M_i of the impactor mass needed to effectively erode a given atmosphere. The latter quantity is heavily dependent, however, on the assumed form of the size distribution $N(d_i)$. To keep the total mass in the impactor distribution finite, we adopt a two-power-law distribution: $dN/dx \propto x^{-2.5}$ for $x < 10$ km, $dN/dx \propto x^{-3.5}$ for $x > 10$ km. An example of a Mars-type calculation is shown in Fig 3. In this case, the ratio $M_i/m_{atm} \sim 3.5$. Preliminary results from out simulations suggest that the “most effective” impactors lie in the range 1 < d_i < 10 km and that M_i varies by factors of order unity from trial to trial, thus requiring a number of trials for statistical determination as a function of the parameter set.

Acknowledgments

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References

[1] McGlaun, J. M., et al., 1990. *Int. J. Impact Engr.* **10**, 351-360. [2] Shuvalov, V., 2009. *Meteorit. Planet. Sci.* **44**, 1095-1105.