EFFICIENCY OF ATMOSPHERIC EROSION BY IMPACTS: ENERGY CONSIDERATIONS AND APPLICATIONS. D. G. Korycansky, *CODEP, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064* .

Introduction

Over the past few years the author and collaborators have been studying mechanisms for atmospheric loss by planets in the Solar System and other planetary systems. One process that we have been investigating is atmospheric erosion by planetary impacts. We have carried out a number of hydrodynamic simulations using the CTH hydrocode from Sandia Laboratory [1]. Our most recent results are presented in a companion abstract for this conference[2].

Shuvalov scaling

Our results have been consistent with the outcome of similar impact calculations by V. Shuvalov[2]. He carried out an extensive set of impact simulations for objects into Mars- and Earth-like targets. He analyzed the results in terms of scaling parameters denoted ξ and χ_a, defined in terms of impactor parameters, target parameters, and the 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.

Plotted as functions of these parameters, Shuvalov's simulation results fell along a curve to which Shuvalov fitted an empirical fifth-order polynomial. The curve peaks at a value of $\xi \sim 400$ with $\chi_a \sim 0.025$. Our results are consistent with the curve, despite in some cases referring to widely different parameters (especially surface gravity, i.e. scale height, and generally higher impact velocities). Thus, it seems likely that impact erosion as a physical process is characterized by this behavior. At this writing we have not yet developed a quantitative explanation for the the curve shape and scaling.

The parameter ξ is can be seen as the ratio of kinetic energies: the characteristic energy at infinity of the impactor striking the surface at velocity v_i *vs.* the kinetic energy of an escaping characteristic mass of atmosphere $\rho_0 H^3$. The Shuvalov parameter χ_a is more readily interpretable as a measure of the efficiency of an impact considered in energy terms. The kinetic energy required to remove a mass m_{esc} from a planet with escape velocity v_{esc} is $1/2 m_{esc} v_{esc}^2$. Similarly the kinetic energy "at infinity" of an impactor of mass m_i that strikes the surface at velocity v_i will be $1/2 m_i (v_i^2 - v_{esc}^2)$. Thus the ratio χ_a is a measure of the efficiency of the process in energy terms. Qualitatively, the peaked form of the curve suggests that both very small impactors and very large (or very energetic) impactors are inefficient at eroding atmospheres. Small impactors (assuming the reach the surface) impart too little energy to accelerate much mass to escape, while for large impactors the energy may be primarily dissipated in target vaporization (for high-velocity impacts) or an "impedance mismatch" may take place (if the the impactor is larger than the atmosphere scale height).

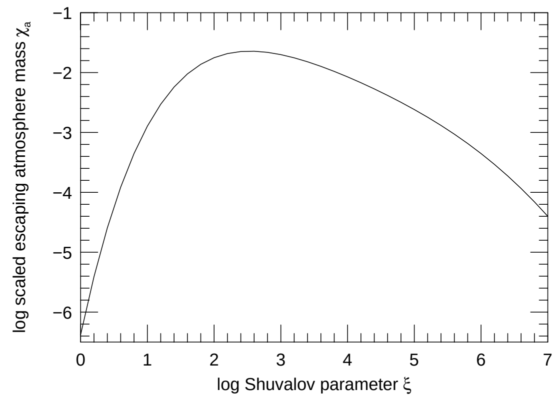

Figure 1: Empirical fit of χ_a *vs.* ξ by Shuvalov[3] to impact erosion simulation results.

v_i (km s^{-1})	d_{opt} (km)	m_{opt} (gm)	m_{tot} (gm)
20.7	27.1	2.9×10^{19}	6.8×10^{24}
41.4	15.8	5.8×10^{18}	1.4×10^{24}
62.2	11.8	2.4×10^{18}	5.9×10^{23}
82.9	9.7	1.3×10^{18}	3.5×10^{23}

Table 1: Given the impact velocity v_i, the table shows the diameter d_{opt}, mass m_{opt} of energy-optimal impactors, and the total impactor mass m_{tot} required to remove the present atmosphere of Venus by impact erosion.

Application to Terraforming of Venus

An application of impact erosion that suggests itself is the terraforming of Venus[4,5]: would it be feasible to use impacts to reduce the atmospheric mass of Venus to a more human-friendly value? Use of the Shuvalov scaling can help provide insight. As noted, the maximum erosional efficiency $\chi_{max} \sim 0.025$ occurs at $\xi \sim 400$. Thus, for a given impact energy at infinity E_∞ (which translates into surface impact velocity v_i, there is an optimal impactor mass m_{opt} (and diameter d_{opt} given an assumed impactor density). For the present-day value of the mass of the atmosphere ($\sim 4.8 \times 10^{23}$ gm) the minimum energy corresponding to optimal impacts $E_{opt} \sim 1.1 \times 10^{37}$ erg. The required number of impacts is also fixed at $N_{opt} \sim 2.4 \times 10^5$. What changes along with the assumed available value of impact velocity at the surface v_i are the impactor masses (diameters) and the total mass of impactors required.

For impact velocities of 2, 4, 6, and $8 \times v_{esc}$ of Venus (10.36 km s^{-1}) we find the results shown in the Table I (where m_{tot} is the total mass required for the erosion). Given that the total mass in the asteroid belt is currently estimated to be $\sim 3 \times 10^{24}$ gm[6], even making use the highest velocity impacts would still require a substantial fraction of the mass of the belt. Additionally, the impactors would all have to be the correct size. A civilization capable of mobilizing mass and energy on the required scale might also be able to dissemble one of the larger asteroids to generate a sufficient number of impactor bodies of the required size, but this would presumably be an additional cost to the project of unknown magnitude.

Acknowledgments

This work was supported by NASA Planetary Atmospheres Program award NNX14AJ45G. DGK thanks F. Souchay for suggesting the application to Venus's atmosphere.

References

[1] McGlaun, J. M., et al., 1990. *Int. J. Impact Engr.* **10**, 351-360. [2] Korycansky et al., 2017. *Lun. Plan. Sci. Conf.* **48**, #1356 [3] Shuvalov, V., 2009. *Meteorit. Planet. Sci.* **44**, 1095-1105. [4] Pollack, J.B. and Sagan, C. 1994, in Lewis, J., Matthews, M., eds. *Resources of Near-Earth Space*. Tucson: University of Arizona Press, 921-950. [5] Landis, G., 2011. Paper AIAA-2011-7215. [6] Piteva, E. V. (2005). *Solar System Research*, **39** 176-186.