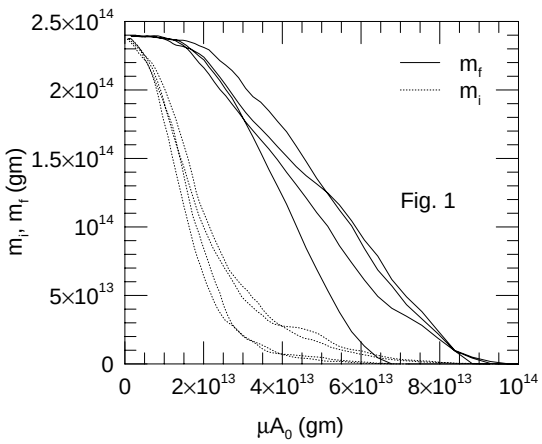
3D SIMULATIONS OF COMET IMPACTS INTO THE ATMOSPHERES OF TITAN AND VENUS. D. G. Korycansky, *CODEP, Department of Earth Sciences, University of California, Santa Cruz CA 95064 USA (kory@es.ucsc.edu)*, K. Zahnle, *245-3 NASA Ames Research Center, Moffett Field CA 94035 USA.*



We present results of three-dimensional numerical hydrodynamical calculations of the impacts of comets into the atmosphere of Titan. Our goal is to develop formulae that may be used to predict the sizes and distributions of craters that are expected to exist on Titan's surface and be found by the Huygens probe of the Cassini mission that will arrive at the Saturn system in 2004. We also compare our results with similar calculations done by us for asteroid impacts into the atmosphere of Venus [Korycansky, Zahnle, and Mac Low 2002 *Icarus*, **157**, 1 (KZM02); Korycansky and Zahnle 2002 *Icarus* in press (KZ03)].

In our most recent work (KZ03), we found that the depth to which the impactor penetrated was governed primarily by the mass of atmosphere encountered by the object, and was otherwise largely independent of other parameters such as impact velocity v_0 and angle θ. The column mass to which the last portion of the impactor penetrates is approximately equal to the mass of impactor at the top of the atmosphere before the impact takes place; however, the impactor is disrupted long before that point, and substantial amounts of mass are stopped in the atmosphere at higher altitudes.

In this work we extend the calculations to i) porous icy bodies such as comets, ii) a different atmosphere (Titan as opposed to Venus) with a different scale height, and iii) a larger range of size (and thus mass): a factor of 10 in size (1000 in mass), spheres ranging from 1 km to 10 km in diameter. Comparison calculations with the Venus atmosphere were also made. As in KZ03, we use a modified version of the ZEUSMP code for the simulations (Norman 2000, *Astrophysical plasmas* eds. J. Arthur *et al.*). The resolution of the calculations is the same as the high-resolutions calculations of KZ03. The impactor material is porous ice, for which we use the Tillotson equation of state (Melosh 1989, *Impact Cratering*). Porosity is treated by the "$p-\alpha$" model (Herrmann 1969, *J. Applied Phys.*, **40**, 2490). We assume an initial 50% porosity, so that the initial density of the impactors is $\rho_0 = 0.46$ gm cm^{-3}. The initial mass of the impactors is denoted by m_0 and the cross-section by A_0; due to ablation and other aerodynamic effects, the mass and cross-section vary as impactor passes through the atmosphere.

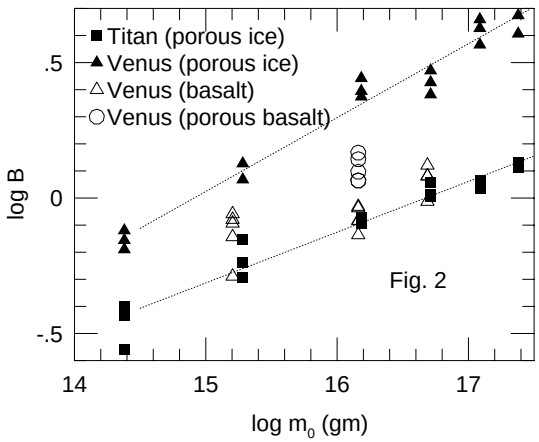
As with previous work, we measure from the simulations as our primary indicators the total mass of the impactor (primary body + ejecta) $m_f(z) = \int dt \int C\rho v_z dA'$ and momentum $q_f(z) = \int dt \int C\rho v_z^2 dA'$ that pass a given height z in the atmosphere; C is a tracer in the simulations that tracks impactor material. [For a given atmosphere $\rho(z)$ and initial impactor cross-section A_0, z translates to column mass $\mu A_0(z) = A_0 \sec\theta \int_z^\infty \rho(z')\, dz'$.] In turn, m_f and q_f can be used to generate a predicted crater size by using a crater scaling such as the one given by Schmidt and Housen (1987, *Int. J. Impact Engineering* **5**, 543). We also track the mass m_i, momentum q_i, and cross-section A_i of the primary impactor body (which loses mass by mechanical ablation due to hydrodynamic instabilities); the impactor body is defined by grid cells with $\rho C > 0.5\rho_0$.

Fig. 1 shows mass curves m_f and m_i versus μA_0 for several 1-km diameter Titan impactors at 10 km s^{-1} impacting at 45°. The calculations differ by ± 0.01 km s^{-1} in their initial velocities in order to sample the effects of sensitivity to initial conditions ("chaos") that we found previously (KZM02, KZ03). For impactors of this cross-section ($A_0 = 7.85 \times 10^9$ cm^2), the surface at $z = 0$ corresponds to a column mass $\mu A_0 = 1.19 \times 10^{14}$ gm, and our calculations predict that 1-km porous icy bodies are completely disrupted at a column mass corresponding to altitudes of ~ 15 km and that the ablated mass is stopped at a column mass $\sim 9 \times 10^{13}$ gm, or about 5 km above the surface, as seen from Fig. 1.

As in KZ03, we can fit empirical formulae for the total masses m_f and momenta q_f of the form

$$m_f = m_0 \left[1 - \left(\frac{\mu A_0}{B m_0}\right)^{\beta_m}\right]^{\alpha_m} \quad q_f = m_0 v_0 \left[1 - \left(\frac{\mu A_0}{B m_0}\right)^{\beta_q}\right]^{\alpha_q}$$

to the m_f and q_f curves, where B, α_m, β_m, α_q, and β_q are fit for each individual run. For the Venus-impact calculations described in KZ03 we found that the parameters such as B were largely independent of m_0, the impactor mass, v_0, its velocity, or θ, the impact angle. Variations were generally smaller than the variance of the result. In this discussion we focus on B; B is the ratio of atmospheric column mass down to which at least some impactor mass penetrates, to the mass of the impactor before it strikes the atmosphere. In other words, given the value $\mu A_0(m_f = 0)$ of the horizontal axis zero-intercept



where $m_f = 0$, B is the ratio $\mu A_0(m_f = 0)/m_0$. Note that m_f is in general not the initial body of the impactor, which suffers ablation and disruption, but the total mass of material, ablated or not, that passes by a given atmospheric height. On general physical considerations, one would expect B to take on values of order unity. However, the situation is complicated by ablation of the impactor; it is possible, for instance, to envision ablative mechanisms that are sufficiently effective as to produce $B < 1$; contrariwise, enhanced aerodynamic effects on ablated material might produce larger values of B. For the Venus calculations (KZ03) we found $B = 0.96 \pm 0.20$, which suggested that rocky impactors (over a range of about 30 in mass) generally penetrate an amount of mass equal to their initial mass.

For porous icy impactors, our results have turned out differently. As can be seen in Fig. 1, the simulations do not yield the value of $B = 0.96$ as can be seen by inspection of the figure; rather $B \sim 0.36$ for these particular runs which are all of impactor mass 2.4×10^{14} gm. We have carried out a suite of simulations of porous icy impactors of a large range of mass, as mentioned above. Large (multi-km) impactors would in reality encounter the surface of Venus or Titan before losing significant amounts of mass (or at least, the total mass would strike the surface); we have therefore extrapolated the atmospheric profiles below the surface level at $z = 0$ in order to focus on atmospheric interactions.

For 19 runs of impactors spanning the range $2.4 \times 10^{14} < m_0 < 2.4 \times 10^{17}$ gm, we find

$$B = 0.49 \left(\frac{m_0}{10^{15} gm} \right)^{0.19} \tag{1}$$

for Titan impactors at 45° and $v_0 = 10$ km s^{-1}. A comparison for Venus porous ice impactors over the same mass range with the same impact velocity and angle yields

$$B = 1.06 \left(\frac{m_0}{10^{15} gm} \right)^{0.27} \tag{2}$$

a result which is consistent with the previous Venus impactor runs (i.e. the results of KZ03), if the power-law variation is neglected; however, a mass ratio of 30 as in KZ03 should lead to a range in B of ~ 2.5, which is rather larger than was observed.

Figure 2 plots log B vs. log m_0 for the calculations described here and relevant calculations from KZ03, along with the fits given by Eqns. (1) and (2). Some conclusions emerge:

- porous and/or icy impactors do have different behavior from rock impactors (e.g. different depths of penetration) in the same atmosphere (Venus)

- porous icy impactors penetrate more deeply into the atmosphere of Venus than into that of Titan by about a factor of 2 in mass; the effect is larger for more massive impactors.

These tentative conclusions require more testing and analysis (e.g. calculations of large rock impactors), but do imply significant additional dependence of mass and momentum fluxes on parameters such as impactor composition (as it affects, e.g. sound speed) and atmospheric profile (e.g. scale height). One possible correlation to be checked is the behavior of the impactor body as a function of atmospheric mass (i.e. m_i). Deposition of mass in the atmosphere is controlled by ablation, which is a function of parameters of the atmosphere as well as the impactor. Ultimately we aim to produce a quantitative explanation of this and other impactor behavior.

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