Initial Conditions of an Impact-Generated Greenhouse Event from Hydrocode Models of Large Impacts on Noachian Mars

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Large impacts have been suggested by Carr [1] and Segura et al. [2], [3] as possible triggers of warm and wet climate episodes on Mars early in its history, when the impactor flux was higher. Here we model large asteroid impacts into stratigraphically detailed models of Noachian Mars [4] in order to constrain the initial conditions, determine a lower bound on the energy and size of impacts that could trigger a climate shift, and establish an upper bound on the frequency of such events.

Background: Carr [1] and Segura et al. [2], [3] propose that heat from large asteroid impacts (100 km $<$ d $<$ 250 km) could have repeatedly broiled the surface and polar caps of Noachian-era Mars, with moderate sized impactors (30 km $< d <$ 100 km) causing smaller or regional effects. This would provide episodic conditions for liquid water on Mars, independent of contemporary solar luminosity. As the surface cooled, the heat from the impact would, according to their models, have caused about 1 meter of precipitation per day for 1-100 years.

There are more than 25 known craters in the correct diameter range that might have caused this level of precipitation [5], and potentially many more craters obscured by other surface processes [6]. The frequency and magnitude of impact generated greenhouse events depends on several factors. The total energy injected into the system is simply the kinetic energy of the impactor plus the gravitational potential energy between the impactor and planet, $E = 1/2mv^2 + GMm/R_p$. Assuming impactor origins in the Noachian were similar to modern sources [7] yields a velocity distribution similar to that calculated by Ivanov [8]. This work describes, through the analysis of impact models, the post-impact mass and energy budget that is available to heat the atmosphere and near-surface regolith.

The efficacy of the impact in triggering greenhouse conditions depends on how much of the impact energy remains in the shallow subsurface near the point of impact, how much is imparted to the deep sub-surface, how much is injected into the atmosphere, and how much escapes to space. A substantial amount of the plume will escape if the radius of the fireball (R_f) grows larger than one atmospheric scale height (H). The radius of the fireball depends on the energy injected into the atmosphere. The minimum energy required for escape has been approximated by $R_f = H = 0.009E_a^{1/3}$, [9]. Where $H \approx 11$ km, $E_a = 1.8 \times 10^{18}$J. For Mars this criterion is predicted to be met at $10 \leq v \leq 15$ km/s, and $m \leq 4 \times 10^{13}$ kg [10].

Calculations of E_a and the more general partitioning of energy between surface and atmosphere require numerical methods. Material that is ejected from the crater with an ejection velocity $\leq v_{esc}$, but not vaporized, will re-impact the surface, transferring heat to areas distant from the point of impact. The sub-surface shock may also mobilize volatiles at the impact site upon release [11].

Impact Models: All of the models for this work were run on two-dimensional axisymmetric grids using the RAGE hydrocode [12] on the LANL QSC and FLASH clusters. The simplest model was a 50 km diameter solid basalt impactor striking a solid basalt surface 6000 km wide by 2845 km thick at 9 km/s, a mesh size chosen so that shocks would not encounter the boundaries at late times. We next ran models with generic stratigraphy, atmosphere, and temperatures appropriate for Noachian Mars, after Nimmo and Tanaka [4] and Catling [13]. These models (figure 1) were run with impactor diameters in the range $10 \text{ km} \leq d \leq 150$ km. Two additional models similar to the generic Mars, but with a near-surface water ice layer or a hydrated tuff permafrost layer, tested the effects of explicitly adding volatiles to the generic model with a 50 km diameter impactor. Twenty models were run in total; not all combinations of parameters were tested due to limitations on available computational resources.

Results: We are interested in the partitioning of energy between the atmosphere (E_a) which indicates the energy available to trigger a greenhouse episode, and the surface (E_s), which indicates the energy available to a potential hydrothermal system. We are also interested in the potential for the subsurface shock and re-impacting ejecta to mobilize volatiles in the target surface, ($V_s(P \lesssim 4.5$ GPa)) and ($M_{ej}(v \leq 5$ km/s)), respectively. This analysis is ongoing for all models. Results for the 50 km diameter impactor are described here, and additional results will be presented at the meeting.

The sub-surface shock expands hemispherically from

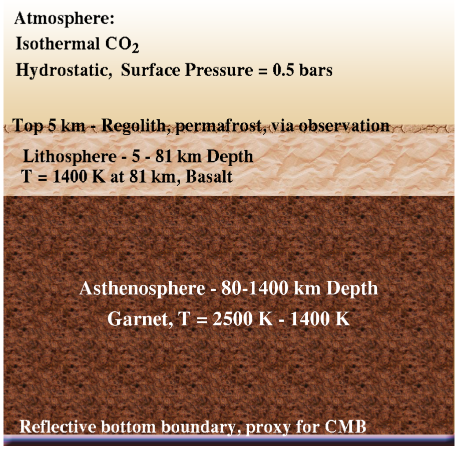

Figure 1: Generic Noachian Mars stratigraphy.

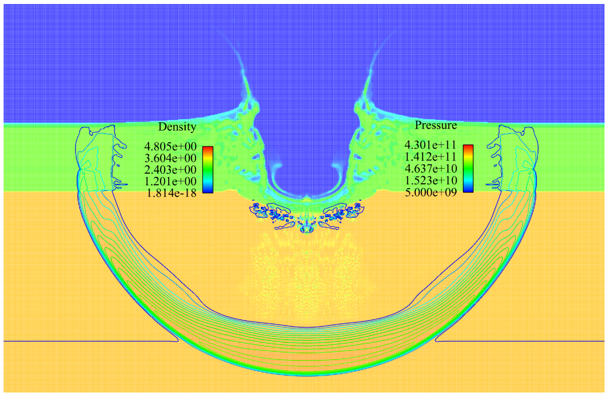

Figure 2: Sub-surface shock in the stratigraphy plotted above, colored by density $[g/cm^3]$ with contours of pressure $[dynes/cm^2]$, $t = 41$ s, $d_i = 50$ km, $v_i = 9$ km/s. The shock front is 233 km from the point of impact.

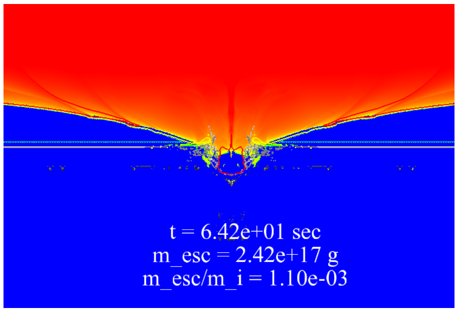

Figure 3: For this impact event $< 1\%$ of the impactor mass escapes the planet, but carries with it of order 10% of the impact energy.

the point of impact as shown in figure 2. The peak shock pressure decays approximately as expected by established crater scaling relations. Approximately 60% of the impact energy propagates deep into the sub-surface where it is sequestered from the atmosphere. The shock pressure in the upper 5 km of the regolith decays below 4.5 GPa within 5 impactor radii of the point of impact for the 50 km diameter impactor, yielding $V_s(P \lesssim 4.5$ GPa$) = 9.8 \times 10^{14}$ m^3 of shocked regolith, which would yield of order 1 meter global equivalent depth of water shocked above the incipient melting point, assuming a 20% mass fraction of water ice in the shocked regolith.

Material ejected from the crater at $v \geq v_{esc} = 5$ km/s escapes the planet. If the vapor plume rising from the impact grows to a radius greater than one atmospheric scale height, it will 'blow out' of the top of the atmosphere. Figure 3 shows $v_y \geq 5$ km/s in red. Although less than one percent of the impactor mass is lost, it is the hottest material, and removes on the order of ten percent of the impact energy.

For the 50 km diameter impactor we find that between $60 - 70\%$ of the initial impact energy is unavailable to an impact-generated greenhouse event. Segura et al. [3] indicate that the remaining energy would be sufficient, but the estimates are close enough that energy budgets must be approached with caution.

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