THE ROLE OF LARGE IMPACTS IN GREENHOUSE WARMING ON EARLY MARS.

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Introduction: The large number of Noachian-aged valley network systems, eroded terrains, and outcrops of aqueously-altered minerals suggests that liquid water was common on the Martian surface early in the planet's history. However, astrophysical models suggest the Sun was only 70% as luminous during this time period [1] which would have made Mars too cold to support liquid water. A variety of models for enhancing greenhouse warming during this time period, both long-term and transient, have been proposed [see review in 2], but their applicability has been questioned.

Recently reduced gases (mainly H_2 and CH_4) have been proposed as a possible solution this faint Sun paradox [3-6], but sources for these gases, such as volcanism from a reduced mantle or serpentinization activity, may not be applicable to early Mars. Here we investigate the role of large impacts early in Martian history, which could deliver organics and iron that can be oxidized in the thermal plume following crater formation to produce the reduced gases.

Methodology: We use the cratering record for Mars to investigate the impact chronology between the 4.2 and 3.7 Ga time period. We utilize the crater data in the Barlow *Catalog of Large Martian Impact Craters*, version 2.0 [7] to identify craters ≥10-km-diameter. We only selected craters superposed on Noachian-aged units and those without ejecta blankets which would indicate a formation age younger than Noachian [8]. We also used Frey's list of Quasi-Circular Depressions [9] to identify features >1000-km-D generally agreed to be impact basins and whose ages straddle the uncertain boundary (~4.1 Gyr) between Noachian and pre-Noachian.

We estimate the original impactor size by first estimating the transient crater diameter (D_t) from [10]

$$D_t = D_{sc}^{0.15} D_c^{0.85}$$

where D_{sc} is the simple-to-complex transition diameter ~7 km) and D_c is the current crater diameter. We then use the relationship between D_t and impactor radius (R) [11]:

$$D_t = \frac{2\rho_m^{0.11} R^{0.13} E^{0.22} (\sin\theta)^{1/3}}{\rho_p^{1/3} g^{0.22}}$$

where ρ_m = density of meteorite = 2000 kg m^3, E = impactor kinetic energy = $(2/3)\pi R^3 \rho_m v^2$, v = average impactor velocity = 10 km s^{-1}, θ = most probable impact angle = 45°, ρ_p = density of basaltic target material = 3000 kg m^3, and g = gravity = 3.7 m s^{-2}. Plugging in these values and equating the above two equations gives the impactor diameter (D) as

$$D = 2(0.00409) D_c^{1/0.79}$$

We randomly assign impactors to various compositions (CI chondrites and H chondrites for asteroids, and 30/70% ice/CI mixture for comets) and, except for craters with reported ages (such as Hellas, Isidis, and Argyre), have a randomized impact chronology. The model estimates the fraction of impactor mass that is converted to H_2 (FH_2) based on the impactor composition (Table 1). We assume a constant surface pressure in each of the simulations, ranging from 0.5 bar to 2 bars, and assume escape of H_2 to space occurs at the diffusion limit, which is the maximum possible escape rate. The model keeps track of the H_2 volume mixing ratio over time, which in turn provides information on the global mean surface temperature [5].

Object	% Converted to H_2 (by mass)	Reference
Asteroids:		
CI chondrites	0.2	[12]
H chondrites	0.04	[13]
Comets:		
(30% ice 70%CI)	0.4	[14]

Table 1: Percentage of impactor mass converted to H_2 for impactors of different compositions.

Results: Figure 1 shows the impact history, H_2 volume mixing ratio, and temperature as a function of time for one of the 1 bar, 0.5% FH_2 simulations. Volume mixing ratios greater than 0.1 result in surface temperatures above 273 K and thus would allow liquid water to be present. The figure shows that volume mixing ratios and temperatures spike dramatically following large impacts but then quickly return to pre-impact values. Investigation of a single large impact such as Hellas shows that the temperature remains above freezing for time scales of 10^3-10^5 yrs. This is an order of magnitude longer than values found previously that looks specifically at energy dissipation from impact events [15, 16] and thus warm, wet conditions can persist for longer periods when H_2 contributions are considered. Our model results show that only impactors larger than about 100-km-diameter can sustain temperatures above freezing for extended periods of time. Only 17 craters/QCDs satisfy this criteria. The cumulative effect of many smaller impacts is insufficient to raise the temperature compared to the impact of a single large bolide and can therefore be ignored.

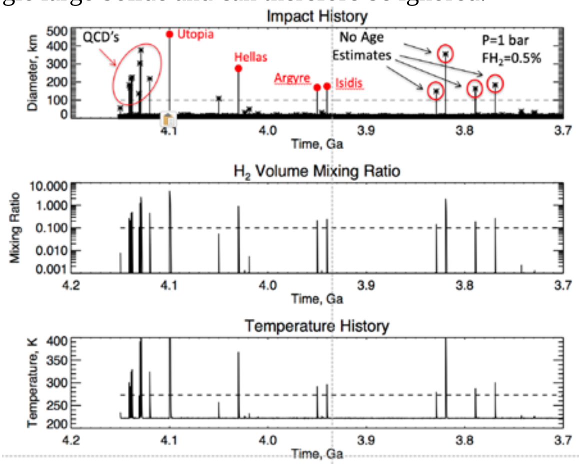

Figure 1: Example simulation of impact history and associated H_2 mixing ratio and surface temperature.

Figure 2 shows how long the temperatures remain above the freezing point of pure H_2O for atmospheric pressures ranging from 0.5 to 2 bars. For a 2 bar atmosphere with FH_2 = 0.5%, Mars can remain above freezing for ~8 Myr whereas for a 0.5 bar atmosphere and FH_2 = 0.1% the time above freezing drops to 0.5 Myr. While these values are only a fraction of the ~400 Myr length of the Noachian period, they do provide significant periods of time when the planet would have been warm enough to support liquid water on the surface.

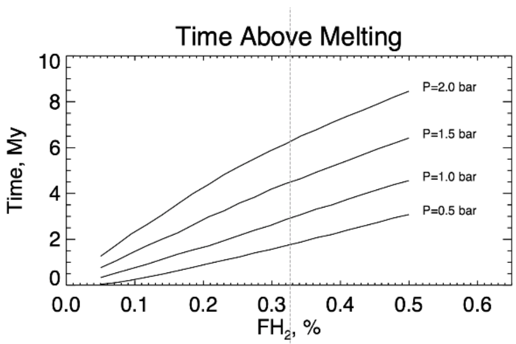

Figure 2: Amount of time surface stays above 273 K for different impactors and atmospheric pressures.

Discussion: Our model simulations indicate that the addition of H_2 into the Martian atmosphere from the thermal plume associated with large impacts can contribute to the greenhouse warming needed to sustain liquid water on the surface of early Mars. Therefore, rather than impacts providing heating through energy dissipation of the impact event itself [15, 16], our results suggest they can raise the surface temperature through greenhouse warming by contributing reduced gases such as H_2.

The strengths of this model are (1) we know that large impacts did occur during this early period of Martian history, (2) our results suggest that the erosional potential is limited but of sufficient magnitude to explain the observed valley networks and eroded craters, and (3) the short-term episodes of high temperature are consistent with the formation time scales of surface clays [17]. The main weaknesses of the model are (1) it requires a pre-existing thick (>0.5 bar) CO_2 atmosphere, (2) it needs a sufficient number of large impactors (>100 km diameter), and (3) it may not explain all the water-related features which formed throughout the Noachian if the large impactors preferentially occurred early.

Our current model is a simple approach to determine whether this mechanism is viable. In future work we plan to extend this model to investigate the contributions from thermal plume chemistry and impactor properties such as size distribution and composition. We plan to conduct 3D simulations of the post-impact environment and escape processes. We also are considering including CH_4 to investigate its contribution to the greenhouse warming.

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