MARS IN THE AFTERMATH OF COLOSSAL IMPACT.

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Introduction: The observed abundances of the highly siderophile elements (HSEs, means "iron loving") are greatly enhanced relative to their predicted quantities in the silicate mantles of Mars [1]. One theory invoked to explain this discrepancy is that the HSEs were delivered after silicate-metal differentiation (i.e. core formation) in the form of a "Late Veneer" (LV) impactor of broadly chondritic composition [2]. According to HSE abundances inferred from martian meteorites, the planet accreted about 0.8 wt% of material of chondritic composition during the late accretion stage [3]. Monte Carlo impact simulations and N-body simulations shows that Mars is expected to have encountered a Ceres-sized object (~1000km across) if it accreted 0.8 wt% during the LV [4]. The existence of the martian northern lowland region (dubbed the Borealis Basin) (e.g. [5]) and martian satellites with coplanar and circular orbits (e.g.[6]) are potential evidences of this hypothetical giant impact. The relatively late formation of the zircons in martian meteorite NWA7034 can be attributed to a LV colossal impact near 4480 Ma that melted a part of the martian crust [7].

A fraction of the impactor's iron core is expected to be fragmented during its collision with Mars [8] and react with the martian surface water reservoir during the pre-Noachian eon (4500-4100 Ma). Isotopic evidences [9,10] and atmospheric mapping [11] indicate that pre-Noachian Mars could possibly have adequate surface water (or surface ice). Reaction between fragmented impactor's iron core and martian surface water could possibly create hydrogen, which is a greenhouse gas [12].

Method: In order to estimate the possibility of an early warm Mars created by LV giant impact, we analyze the fate of an iron core from a leftover Ceres-sized planetary embryo striking Mars during the LV. Our study employs SPH impact simulations as well as analytical estimations of the post-collision evolution of the impactor's core materials with a postulated hydrosphere (or cryosphere) on pre-Noachian Mars.

SPH simulation results: We performed SPH impact simulations between a differentiated Ceres-sized impactor colliding with Mars with impact velocities, v_{imp} = 7 to 16 km/s and impact angles, $\theta = 0^{\circ}$ to 60°. Figure 1 shows the statistic of the collision outcome for the impactor's iron core. We found that >90% of the impactor's core materials are bound to Mars after the collision until $\theta \geq 50^{\circ}$. These bound iron material enrich martian mantle with HSEs. The shaded region in Figure 1 indicate the fraction of fragmented impactor's iron core that is bound to Mars after the giant impact. About half of the impactor's iron core (3×10^{19} kg) is fragmented and bound to Mars after the collision when $\theta = 45^{\circ}$ to 50°. These fragmented iron could possibly react with martian surface water and generate hydrogen. We estimated the size of the molten iron fragments, d, by the following equation:

$$d = \left(\frac{40\sigma}{\rho\dot{\varepsilon}^2}\right)^{1/3} \qquad (1)$$

[13], where $\dot{\varepsilon}$ is the strain rate of the expanding molten iron blob, ρ = 7000 kg/m^3 is the density of the iron droplets and σ = 2 N/m is the surface tension for liquid iron [14]. In the statistically mostly likely case ($\theta = 45^{\circ}$), $d \sim$ 10 m. These 10 m iron fragments then further fragmented into ~6 mm iron hail when they finally settle on the surface of Mars.

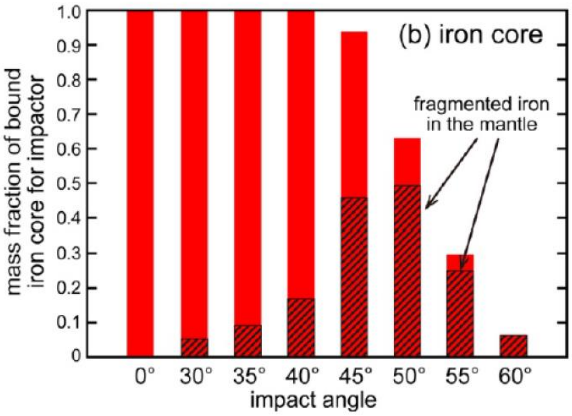

Figure 1. Mass fraction of impactor's iron core that is gravitationally bound to Mars after collisions as a function of impact angle, θ. The impact velocity, v_{imp}, is the same for all θ (10 km/s).

Implication – impact generated H_2 atmosphere: These 6 mm iron fragments could thus react with the postulated surface water reservoir on Mars and generate 3 bar H_2, which is thick enough to keep the early martian surface temperature above water's freezing point

[15,16]. This early H_2 atmosphere, however, is tenuous. The more intense extreme ultraviolet (EUV) of the young sun leads to the rapid escape of the hydrogen atmosphere through the process of hydrodynamic escape [17,18]. The escape flux of hydrogen, $\phi_{\mathrm{H_2}}$, is be estimated by

$$\phi_{\mathrm{H_2}} = \frac{\varepsilon_{\mathrm{eff}} f_{\mathrm{EUV}}(t) R}{4GMm_{\mathrm{H_2}}}\ [\mathrm{m^{-2}s^{-1}}] \qquad (2)$$

[19], where G is the gravitational constant, R is the planetary radius, M is the planetary mass and m_{H2} is the molecular mass of H_2, $f_{\mathrm{EUV}}(t)$ is the EUV energy flux received by Mars [20] and $\varepsilon_{\mathrm{eff}} = 0.3$ is the escape efficiency. We estimated that the H_2 atmosphere would be fully escaped within 3 Myr by integrating Equation (2). Assuming the young sun as a slow rotator and hence around 5 times weaker $f_{\mathrm{EUV}}(t)$ [21] would extend the life time of the H_2 atmosphere to ~10 Myr. Alternatively, if CO_2 existed before the LV giant impact, $\varepsilon_{\mathrm{eff}}$ of the hydrodynamic escape would be lower due to 15 µm band infrared emission of CO_2 [18] and therefore the life time of H_2 could possibly be extended.

Future work: Given the greenhouse nature of hydrogen gas and its implication for biopoesis on early Hadean Earth (e.g.[22],[23]), we call for further study on the possible generation of an early hydrogen atmosphere and its effect on the surface temperature of pre-Noachian Mars through more detailed hydrodynamical atmospheric models. The model should consider different Solar EUV evolution and different mixing ratio of hydrogen in CO_2 atmosphere.

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