GIANT IMPACTS ON EARLY MARS AND THE CESSATION OF THE MARTIAN DYNAMO.

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Introduction: Although Mars currently has no global magnetic field, the widespread crustal magnetization [1] provides strong evidence that such a field existed in the past. The absence of magnetization in the younger large Noachian basins suggests that a dynamo operated during the early to mid-Noachian [2], but stopped once the heat flow became unfavorable for core convection. The critical heat flux is not well known, but is estimated to be 5-17 mW m^{-2} (0.2-0.6 TW global heat flow) from modeling studies [3]. Within a 100 Ma period, a series of 15 giant impacts occured [4], the end of which coincides with the dissaperance of the global magnetic field [5]. Here we investigate a possible link between the giant impacts during the early and mid-Noachian and the cessation of the Martian dynamo at about the same time.

Basin Ages and magnetization: Quasi-circular depressions (QCDs) identified in MOLA topography [6] and circular thin-crust areas (CTAs) identified in crustal thickness maps [7] have been associated with both exposed and buried impact structures [4]. The combined population of QCDs and CTAs provides the best estimate available of the N(300) crater retention ages (CRAs) for large Martian basins [4]. N(x) is the cumulative number of superimposed craters of diameter > x km per 10^6 km^2. CRAs show a strong clustering between N(300) = 2.5 and 4.0 (or 4.1 and 4.2 Gyr in model age [8]), implying a 'peak' in crater production. We take from [4] the times, locations and sizes of 20 giant impacts. As shown in Fig. 1 [5], the 14 oldest basins are all much more strongly magnetized than the 6 youngest basins are all demagnetized, suggesting that the dynamo shut down at the time of this transition. The Utopia basin is the largest of these 20 basins and probably the oldest to be demagnetized [5].

Impact Heating: Giant impacts can introduce a substantial amount of heat into the interior of the planet. We use scaling relations to to obtain the transient basin diameters from the observed final basin sizes, D [9], and to obtain the impactor size from the transient basins [10], assuming an impactor velocity of 15 km/s. A significant fraction of the impactor's kinetic energy will be converted to thermal energy, raising the temperature of the surrounding mantle. The mantle is heated by a shock wave emanatimg from the impact location. Heating is uniform within an isobaric core, which scales with the impactor size and decays rapidly outside this region. We parameterize the impact heating as a temperature perturbation in the mantle, which is a function of the shock pressure [11].

Convection Model: We model thermal convection in the Martian mantle usinng the 3D spherical finite-element convection code CitcomS [12], using a temperature- and pressure-dependent viscosity. We apply isothermal and free-slip boundary conditions at the surface and core-mantle boundary (CMB), and include internal heating from radioactive decay. At the times indicated by the impact age model [4], we apply an instantaneous temperature increase as determined above [9-11]. Each model was run for a few Ga, until well after the giant impacts had occured. For each case, we also ran a control case without the impact heating applied in order to examine the effect the impacts have on the thermal evolution. More details on the methodology are provided in [13].

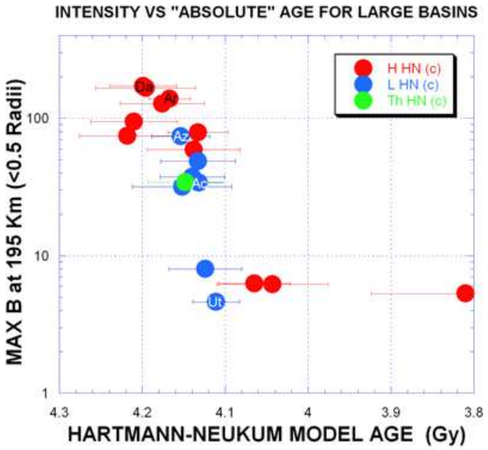

Figure 1: Magnetic field intensity vs. model age for giant impact basins on Mars. See [5] for more details. The colors code denotes the region each basin is found on: Highlands (red), Lowlands (blue) or Tharsis (green). The five largest basins ($D > 2500$ km) are labeled (Da: Daedalia, Ar: Ares, Az: Amazonis, Ac: Acidalia, Ut: Utopia).

Results: The global heat flow at the surface and the CMB for two pairs models are shown in Fig. 2. While every impact causes a spike in the heat flow at the surface, the CMB is only affected by the very largest impactors ($D > 2500$ km). These impacts (e.g. Utopia) can reduce the CMB heat flow by 10-40 % depending on the Rayleigh number, Ra. Note that the background CMB heat flow is consistent with the range of values needed to sustain core convection [3]. In Fig. 3, we show a cross-section of the temperature profile at the time of the Utopia impact. The temperature increase is strongest within the isobaric core and decays rapidly with distance. Only the very largest impacts cause significant heating at the CMB and reduce the CMB heat flow.

While the CMB heat flow is reduced immediately after the impact, it recovers as the thermal anomaly is advected away. Furthermore, since the impact heating creates lateral temperature variations, the buoyancy of the heated region is increased, and the heat flow may increase above the pre-impact level. For all cases shown here, the recovery time is longer than the interval between giant impacts during the period of most

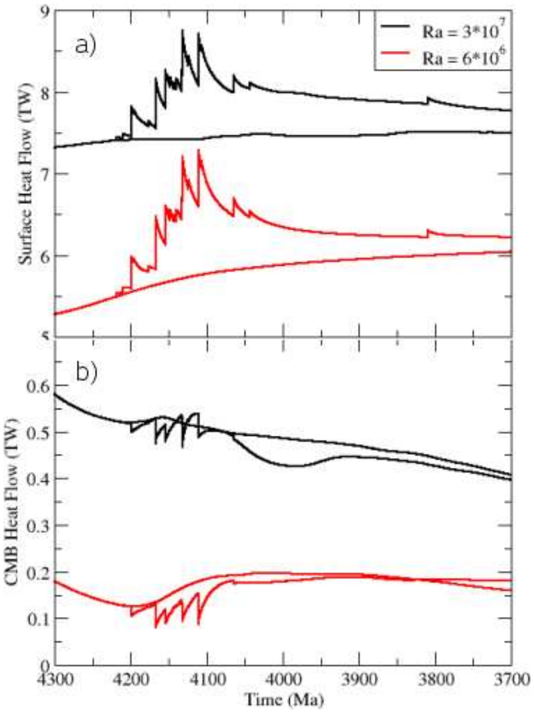

Figure 2: Total global heat flow at the surface (a) and CMB (b) vs. time for Ra = 3.05×10^7 (black) and Ra = 6.1×10^6 (red). Each impact causes a strong perturbation to the surface heat flow. Relatively little heat is deposited at large depths. Only impactors forming basins $>$ 2500 km in diameter cause a significant drop in the CMB heat flow, but these drops can be large ($> 10 - 40\%$).

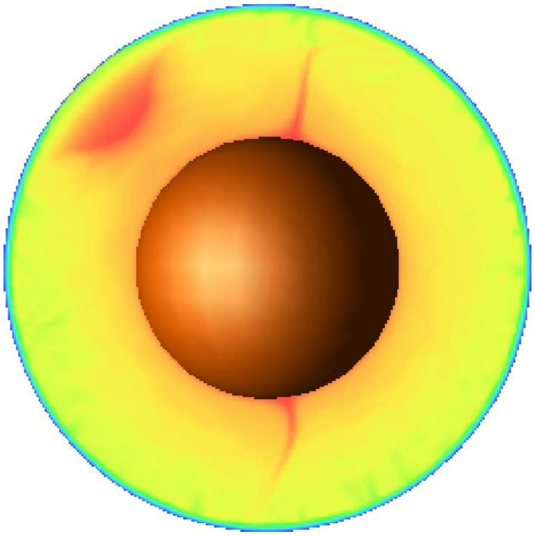

Figure 3: Cross-section of the mantle temperature profile immediately after the Utopia impact. Color scale shows warmest regions in red, coolest in blue.

intense bombardment (4.2-4.1 Ga). However, we note that Ra is an important control on this recovery. In the high-Ra case, the thermal anomaly is advected away relatively quickly, and the heat flow increases above the pre-impact level. In the low-Ra case, heat flow does not recover fully, and each subsequent impact pushes it lower.

Discussion: Recent simulations of subcritical dyanamos [14] suggest that, if core heat flow is slightly above the subcritical threshold, a drop of 1% in core heat flow can cause the strength of the magnetic field to drop by 3-4 orders of magnitude, a perturbation easily produced by giant impacts. Furthermore, if a subcritical dynamo is stopped, it cannot restart upon restoration of the initial heat flow state; an increase of 25% above this level is required for re-initiation of dynamo activity. Such an increase is difficult to justify geologically. Thus, if the Martian dynamo were subcritical at the time of the Utopia impact (and the dynamo must has passed through a subcritical stage at some point before its cessation), the impact heating from the Late Heavy Bombardment may have been sufficient to shut down the dynamo permanently.

However, the drop in CMB heat flow of up to 40% seen in our models is sufficient to shut down even a supercritical dynamo. While the dynamo activity may be restored once the thermal pulse dissipates, the resulting magnetic field will not necessarily come back at the same strength. We note that each of the five largest basins (with $D > 2500$ km have a significantly weaker magnetization than the next oldest (see labeled points in Fig. 1. We suggest that each of these impacts may have temporarily shut down the magnetic field, and that each time the field did not recover fully. By the time of Utopia, the field was sufficiently weakened that the last of these impacts shut it down permanently.

The loss of the magnetic field exposed the Martian atmosphere to eroision by the solar wind, and a change in the Martian climate and geochemistry would be expected. Mineralogy observed with OMEGA is consistent with a climatic shift from wet to drier, more acidic conditions (the Phyllosian-Theiikian transition) prior to $\sim$ 3.9 Ga [15], and likely after the dynamo is thought to have shut down.

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