EFFECTS OF BASIN-FORMING IMPACTS ON THE HISTORICAL MARTIAN DYNAMO.

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Introduction: Mars had an active dynamo in its early history [1,2], evidenced by the strong remanent crustal field observed by Mars Global Surveyor [3]. Recent studies [4] show a strong correlation between the timing of the dynamo termination and giant impacts (forming basins greater than 1000 km in diameter) during the mid-Noachian period. Further modeling studies suggest that such impacts could generate a strong thermal heterogeneity in the deep interior. The correlation in the timing may not be accidental: the giant impacts could play a critical role in terminating the Martian dynamo via, e.g., a small uniform perturbation permanently ending a subcritical dynamo [5], or a strong thermal heterogeneity destroying a subcritical dynamo.

To better understand the effects of basin-forming impacts on Martian dynamo, we simulate the Martian dynamo with a heterogeneous heat flux across the core mantle boundary (CMB) arising from the shock heating of these impacts (e.g., Utopia). Our research aims at understanding whether such thermal heterogeneity is fatal to the dynamo, and how it changes the dynamo properties. Our results show that both the location and the intensity of the heterogeneity of the heat flux across CMB may have significant effects on the subcritical Martian dynamo.

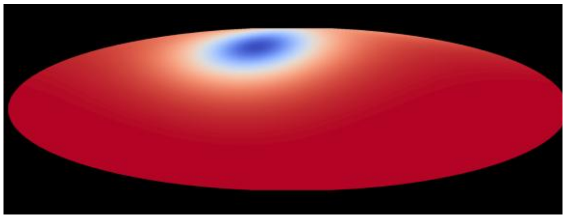

Figure 1 Heat flux perturbation at the CMB due to a Utopia-forming impact. Other impacts will generate similar heat flux anomalies, but with different impact locations.

Mathematical Model: In this study, we first consider heating of the Martian mantle by basin-forming impacts. Following Roberts et al. [6], we use scaling relations to obtain the projectile size D_p from a given basin size D_b [7,8], assuming an average impactor velocity, v_i of 10 km/s [9]. The mantle is heated by a shock wave emanating from the impact location. The shock pressure, P_s is nearly uniform within an isobaric core, and decays rapidly with distance r away from this region [10]. We parameterize the impact heating as a temperature perturbation ΔT in the mantle, which is a function of the shock pressure, using foundering shock heating model of Watters et al. [11]. We then compute the change in heat flux at the CMB as a result of this temperature perturbation. See [6,12] for more details. Figure 1 shows this heat flux perturbation for a Utopia-forming impactor (D_b = 3380 km).

The numerical dynamo model used in the study is developed by Jiang and Kuang[13] with one modification: a sixth-order compact finite difference scheme in radial dimension replaces the old fourth order scheme in the model, in addition to some other minor modifications. The parameter values are the same as those in [5], but with a higher resolution (100×200×250 in r, θ and φ). In our simulation, we decomposed the temperature profile T into three parts,

$$T(t,r,\theta,\varphi) = T_0(r) + T_1(r,\theta,\varphi) + \Theta(t,r,\theta,\varphi)$$

where T_0 is a uniform steady conducting temperature and T_1 is a steady conducting temperature perturbation that agrees with the given heat flux heterogeneity across the CMB, is the unsteady part. T_1 satisfies the equation,

$$\nabla^2 T_1 = 0$$

and the heterogeneous heat flux boundary conditions (Figure 1),

$$\left(\frac{\partial T_1}{\partial r}\right)_{r=r_{cmb}} = -\varepsilon \sum_{l,m} h_l^m Y_l^m(\theta,\varphi)$$

where ε is an intensity scaling factor and changes in our numerical simulation. In addition, we consider only the impact location changes in the latitude without loss of generality. Normally T_1 can be decomposed as,

$$T_1(\theta,\varphi) = \sum_{l,m} T_{1,l}^m Y_l^m(\theta,\varphi) \; . \qquad (1)$$

By choosing the homogeneous heat flux across the inner core boundary (ICB), i.e.,

$$\left(\frac{\partial T_{1,l}^m}{\partial r}\right)_{r=r_{icb}} = 0 ,$$

we can have analytical solution of T_1. With T_0 + T_1 as the background state in the simulation, the temperature perturbation Θ satisfies the homogeneous boundary conditions at both ICB and CMB. The details about momentum equations and induction equations can be found in [13].

Numerical Results: Figure 1 shows the heterogeneous flux at CMB caused by the Utopian basin-forming impact. The red color represents heat flux out of the CMB and blue color represents heat flux into the CMB. To find the subcritical value for the dynamo, i.e., the minimum Rayleigh number (*Ra*) required to sustain a strong field dynamo, we gradually reduce *Ra* from a value with a super-critical, strong-field dynamo solution, using the simulation results of earlier Rayleigh numbers as the initial condition for the simulation with the new *Ra*. Figure 2 shows that the strong field dynamo suddenly disappeared around *Ra* ≈ 1900. By using the simulation results at *Ra* = 1900 (non-dynamo solutions) as the initial condition, simulation results show that a strong field dynamo is excited when *Ra* is greater than 2800(see Figure 3). We estimate from these results that the subcritical dynamo domain for the Rayleigh number *Ra* is from 1950 to 2700 (these values are slightly different from our earlier results [5] due to different numerical resolutions and algorithms).

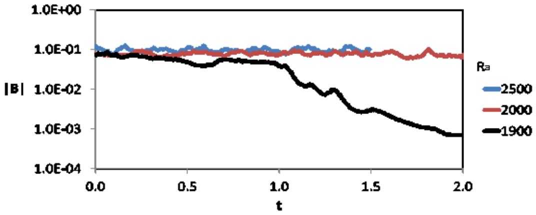

Figure 2. The strong field dynamo disappeared when Rayleigh number *Ra* is smaller than 1900

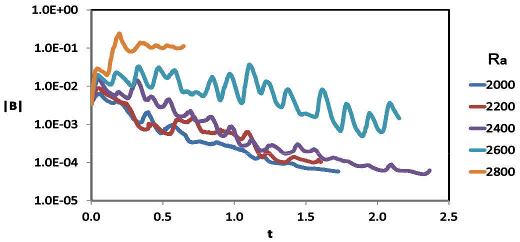

Figure 3. The strong field dynamo is excited when Rayleigh number *Ra* is greater than 2800.

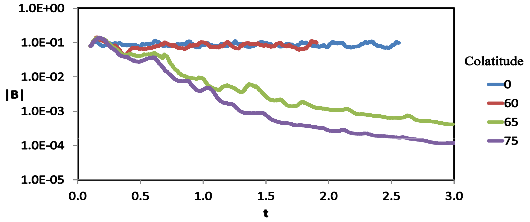

Figure 4 . The subcritical dynamo disappeared when the centers of the impact are close to the equatorial region.

To study the effects of the thermal heterogeneity (1) on subcritical dynamos, we focus on the solutions with *Ra*=2000. As shown in Figure 4, the subcritical dynamo state can be destroyed by the heterogeneity with the center location within 25° from the equator. Conversely, if the center is close to the polar region (60° and higher), the subcritical dynamo still exists, though the field strength may change slightly. The heterogeneity intensity $\varepsilon = 0.85$ in Figure 4.

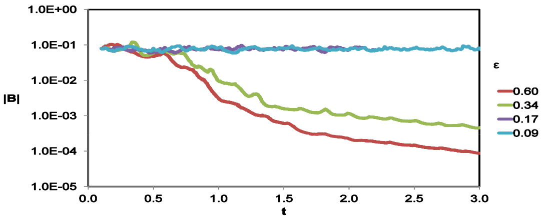

Figure 5. . The subcritical dynamo disappeared when the intensity of the heterogeneity ε is greater that 0.34.

Given the epicenter on the equator, we also considered different intensity values. And the results are shown in Figure 5. We find that if the intensity is small enough (i.e., ε<=0.17), the impact is not able to kill the subcritical dynamo.

Discussion: Subcritical dynamo solutions are sensitive to the CMB heat flux heterogeneity. The location of the anomaly plays a strong role in terminating a subcritical dynamo: the closer the anomaly's center to the equator, the more likely it would destroy the dynamo. Numerical results suggest that given the magnitude of the thermal heterogeneity, there is a finite region around the equator ("death zone") such that, the subcritical dynamo will be terminated if the anomaly center is within this region. The magnitude of the heat flux anomaly also plays an important role. Numerical solutions suggest that this death zone expands with the anomaly magnitude. These findings provide further magnetic constraints on Martian evolution history, e.g. paleo locations of impacts and other thermal heterogeneity sources.

References: [1] Acuña, M. H. et al. (1999), *Science*, **284**, 790-793. [2] Arkani-Hamed, J. and D. Boutin (2004), *JGR*, **109**, E03011. [3] Acuña, M. H. et al. (2001), *JGR*, **106**, 23,403-23,417. [4] Lillis, R. J. et al. (2008), *GRL*, **35**, L14203. [5] Kuang, et al.,(2008), *GRL*,35 , L14204. [6] Roberts, J. H. et al. (2009), *JGR*, 114, E04009. [7] Holsapple, K. A. (1993), *Ann. Rev. Earth Planet Sci.*, 21, 333-373. [8] Melosh, H. J. (1989), *Impact Cratering*, Oxford Univ. Press, 253 pp. [9] Neukum, G., and D.V. Wise (1976), *Science* 194, 1381–1387. [10] Pierazzo, E. P. et al. (1997), *Icarus*, 127, 208-223. [11] Watters, W. et al. (2009), *JGR*. 114, E02001. [12] Roberts, J. H. and J. Arkani-Hamed (2012), *JGR*, in press. [13] Jiang,W. and W. Kuang (2008), *PEPI*, 170, 46-51