GIANT IMPACTS AND THE DEATH OF THE MARTIAN DYNAMO: WHERE DATA MEET MODELS.

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Introduction: Present-day Mars does not possess an active core dynamo and associated global magnetic field. However, the presence of intensely magnetized crust implies that a Martian dynamo has existed in the past [1, 2]. By analyzing the crustal magnetic field signatures and crater retention ages (CRAs) of ~20 giant impact basins, we can determine the time at which, and duration over which, the Martian Dynamo ceased. We can place this quantitatively in the context of Mars' early history by simulating 1) the effect of such giant impacts on the core heat flow and 2) the response of the core dynamo to the resulting perturbations.

Crater retention ages of basins. Quasi-circular depressions (QCDs) identified in MOLA topography [3] and circular thin-crust areas (CTAs) identified in crustal thickness maps [4] have been interpreted as buried impact structures [5]. The combined population of QCDs and CTAs provides the best estimate available of the N(300) crater retention ages (CRAs) for large martian basins [5]; N(x) is the cumulative number of superimposed craters of diameter > x km per 10^6 km^2. CRAs show clustering between N(300) = 2.5 and 4.0 (or 4.1 and 4.2 Gyr in absolute model age [6]), as shown in fig. 1. Such a peak in crater retention ages, if indicative of formation ages, may imply a 'spike' in the large object impact rate , perhaps similar to the proposed "terminal lunar cataclysm" suggested by the ages of large lunar basins and the relative absence of lunar sample ages > 4.0 Gyr [7].

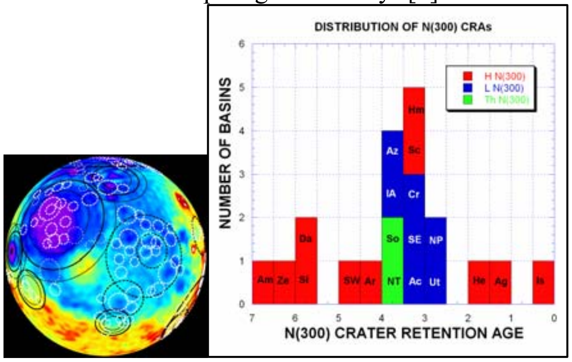

Fig. 1: crustal thickness data with superimposed CTAs (left) and distribution of N(300) CRAs (right).

Magnetic signatures of basins: a large meteorite impact can alter the magnetization of the entire depth of crust over an area comparable to the final size of the impact basin [8]. Magnetization can be removed through excavation, shock and heating. The crust can also acquire thermoremanent or shock remanent magnetization (TRM or SRM) aligned with the direction of, and with a magnitude dependent on the strength of, the local ambient magnetic field at the time of impact. Magnetization acquired through SRM or TRM (or lack thereof) is preserved in the crust and can be detected by spacecraft measurements of magnetic field. Here we use the electron reflection (ER) map of crustal magnetic field at 185 km altitude [9] or *B185*. Simple calculations show that, for any plausible magnetic coherence scale, *B185* is a reliable proxy for magnetization for basins >1000 km in diameter. If we assume that remanent coercivity does not vary globally by factors of more than several, if we allow for differences in crustal thickness and if we exclude areas where the magnetization has been subsequently altered by volcanic or impact processes, *B185* measured above a basin (or more specifically its maximum value within 0.5 basin radii, $B185_{max}$) corresponds approximately to the strength of the magnetizing field at impact.

Timeline for the Martian Dynamo. Figure 2A plots $B185_{max}$ vs. CRA for the 20 largest basins on Mars. Despite uncertainties in the CRAs, there appears to be a consistent separation in age between the mostly magnetized and mostly demagnetized basins, clearly separating dynamo from post-dynamo epochs. Further, by analyzing the Poisson distribution of each basin CRA and demanding that all magnetized basins formed prior to all demagnetized basins (fig. 2B), we can calculate relative probabilities for the time at which, and interval over which, the Martian dynamo ceased. As shown in fig. 2D, we find (80%, 50%, 25%, 10%) probability that the dynamo cessation took less than (20, 10, 5, 2) Myr respectively.

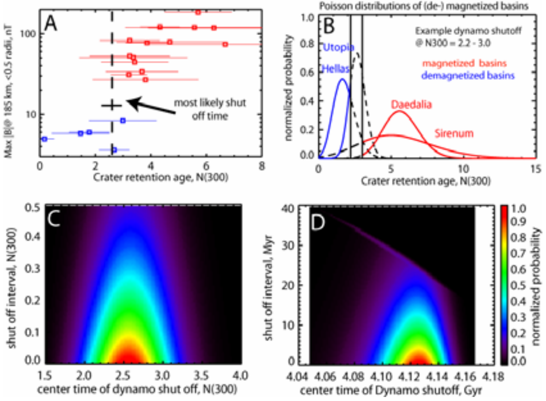

Fig. 2: dynamo timeline & cessation probabilities (see text)

Subcritical dynamo modeling: simulating the end of the Martian dynamo. Is such a geologically rapid dynamo cessation plausible? We can shed light on this question by the fully nonlinear, 3-D numerical simulation of dynamo action in the Martian core[10]. In this model, the buoyancy force (that drives the dynamo) is assumed thermal: its strength can be measured by the (super adiabatic) heat flux across the core-mantle boundary (CMB); which is characterized by the Rayleigh number R_{th} in the model. We find that the dynamo exists for $R_{th} \geq 2460$; it disappears for $R_{th} \leq 2440$, as shown in fig. 3. Further, reactivating dynamo action is not possible until the Rayleigh number is increased to $R_{th} \approx 2800$, hence this dynamo is subcritical. The simulation results suggest that if the Mars dynamo was in its subcritical state, then it could be terminated by a small reduction (~1%) in the buoyancy force. Dynamo reactivation of dynamo is impossible unless there is a significant increase (~20%) in the buoyancy force.

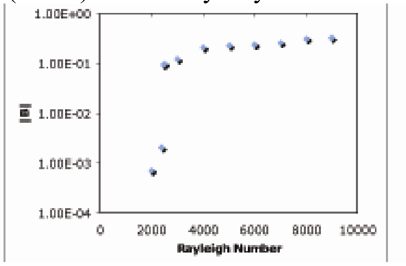

Fig 3: dimensionless magnetic field strength at the martian surface as a function of thermal Rayleigh number.

Too good a coincidence to be one? If the martian dynamo died quickly and if this termination 1) required only a small reduction in the core-mantle heat flow *and* 2) occurred immediately after ~10-15 giant impacts, the question must be asked: could the martian Late Heavy Bombardment have killed the dynamo?

Modeling impact effects on mantle convection. To answer this question, we performed thermal convection simulations of the Martian mantle using the 3D spherical finite-element convection code CitcomS [11], using a temperature- and pressure-dependent viscosity. The 20 aforementioned impacts were simulated by instantaneous temperature increases of 300 K inside hemispherical regions [12] at the appropriate times and locations. The model was run for several hundred Ma, until after the Utopia impact.

Figure 4 shows the time evolution of the global heat flow at the surface and core-mantle boundary (CMB) for cases with and without impacts. A basal heat flow of about 1 TW persists for the duration of the calculations which may be enough to drive a core dynamo [13, 14]. The larger impacts raise surface heat flux by 1-2 TW over a period on the order of 20 Ma. The impacts generate large horizontal temperature differences and hence buoyancy in the mantle, causing more vigorous convection, but this cooling effect is more than compensated for by mantle heating and the result is a 2% decrease in total heat flow across the CMB in the impact-heated case relative to a control case with no impacts.

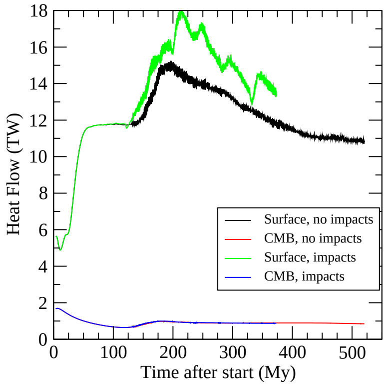

Figure 4:surface and CMB heat fluxes with and without impacts plotted as a function of time.

In order for the impacts to stop the dynamo, the dynamo must have been subcritical so that a small decrease in total heat flow, resulting in a possibly much larger decrease in superadiabatic heat flow, could have stopped core convection probably several tens of Myr earlier than would otherwise be the case.

Conclusions. Crater retention ages derived from QCDs and CTAs imply a 'spike' in cratering on Mars akin to the proposed 'terminal lunar cataclysm' on the Moon. Analysis of the magnetic field signatures of these basins shows that the Dynamo terminated immediately following this 'spike' and over a short interval, <~10 Myr., consistent with numerical simulations of subcritical dynamos. However, due to uncertainties in superadiabatic heat flow, the conjecture of a strong causal link between the Noachian giant impacts and the cessation of the Martian dynamo cannot be conclusively supported by our thus-far limited modeling of the effects on mantle convection of these impacts. Work continues to explore model parameter space in order to resolve these uncertainties and determine whether the similar timing could be a coincidence.

References: [1] M.H. Acuna et al., *Science* (1999), [2] J.E.P Connerney, *Science* (1999), [3] M. D. Smith et al., *JGR* (2001) [4] Neumann et al., *JGR* (2004), [5] Frey et al., *7th Mars conf.* (2007), [6] W.K. Hartmann & G. Neukum, *Space Science Reviews,* (2001) [7] Tera, F. et al., EPSL (1974), [8] Hood et al., GRL (2003), [9] Lillis et al., *Icarus* [10]Kuang et al., LPSC (2007), [11] Zhong et al. (2000) *JGR, 105*, 11,063-11,082. [12] Reese, Solomatov (2002) JGR, 107,E10, [13] Nimmo F. and Stevenson D. J. (2000) *JGR, 105,* 11,969- 11,979., [14] Buffett, (2002) *GRL, 29,* 1566.