NUMERICAL SIMULATION OF HISTORICAL MARTIAN DYNAMO: ONSET AND ANNIHILATION OF THE DYNAMO ACTION

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Summary: Mars possessed a strong magnetic field originated from its interior (the internal magnetic field). This field was generated and maintained by convective flow in the electrically conducting liquid core. The termination (annihilation) of the Martian dynamo, in particular the energy necessary to maintain the dynamo action, is not well understood. Our numerical simulation of Martian dynamo suggests that the annihilation of the dynamo action can be abrupt, and subcritical (i.e. at an energy budget lower than that required for onset of dynamo).

Introduction: One important finding of the Mars Global Surveyor (MGS) mission is the strong magnetization in the highland crust of the Martian southern hemisphere [1]. This finding suggests that Mars once had an active, strong-field dynamo in its early evolution history. However, it is not very clear on the timing of the Martian dynamo, in particular the time when the dynamo action stopped operating in the core [2,3]. The answer to this question depends on many geodynamical processes in the core and in the mantle of the Mars. For example, mantle convection determines the cooling rate of the planet over its history, and therefore the energy source available for the dynamo action in the core.

The more fundamental question is how much energy is required to sustain a dynamo action in the core? Traditional dynamo studies focus on the conditions (critical points) for the onset of the dynamo. But the termination of the Martian dynamo is opposite: a strong-field dynamo action was already established in the core. It stopped because of the slowing down of the cooling (thus reduction of energy source) of the planet.

Theoretical studies in non-planetary geometries suggest that the onset (forward) and the annihilation (reverse) of a dynamo action can follow different tracks [4]. In particular, a strong-field dynamo, once established, may exist even if the driving force is lower than that required for the onset of the dynamo (sub-critical dynamo). This subcritical process, if exists in the Martian core, would determine not only the extinction time of the Martian dynamo, but also the termination process (a sudden death over a short period or a gradual reduction of the internal field strength) and the field properties during the termination period.

Numerical Simulation: We study the dynamo onset and annihilation via numerical simulation. The model is self-consistent, fully non-linear and three-dimensional (for a spherical shell) [5,6]. In addition to the fluid shell, a solid electrically conducting inner core and a solid electrically conducting layer at the bottom of the mantle are included in the model. Therefore the geometry of the core is determined by the core-mantle boundary (CMB) radius \( r_{icb} = 1 \) (due to spatial scaling) and the inner core boundary (ICB) radius \( r_{icb} \). The physical properties of the Martian core are described by the nondimensional magnetic Rossby number \( R_e \), the Ekman number \( E \) and the magnetic Prandtl number \( q_m \) [5]. The driving force of the dynamo is the buoyancy force arising from temperature (or compositional) difference across the outer core and is measured by the nondimensional Rayleigh number \( R_{th} \).

In our numerical simulation, the parameters are specified as \( E = R_e = 1.25 \times 10^{-6} \) (approximately \( 10^{-8} \) in the Mars core) and \( q_m = 1 \). Two inner core radius values \( r_{icb} = 0.35 \) and \( r_{icb} = 0.1 \) are selected in simulation to understand the effect of the core geometry on the onset and the annihilation of the dynamo. The Rayleigh number \( R_{th} \) varies in the numerical simulation. For the forward process (onset of dynamo), \( R_{th} \) increases gradually from an initial subcritical value (no dynamo exists) to a large value when a strong field dynamo is established. For the reverse process, \( R_{th} \) decreases gradually from an initial supercritical value (when a strong field dynamo exists) to a small subcritical value.

For each given Rayleigh number \( R_{th} \) simulation is carried out until the numerical solution stabilizes (i.e. well past the transient period). The initial solution is chosen from the well-established numerical results of the (immediate) previous Rayleigh number to ensure that the variation of the dynamo process with the Rayleigh number is carefully followed.

Results: We have carried out the all necessary numerical simulations for the reverse process with \( r_{icb} = 0.35 \). The Rayleigh number \( R_{th} \) decreases from \( R_{th} = 15000 \) (when a strong field dynamo exists [7]) to \( R_{th} = 2000 \). Numerical simulations for the forward process are still to be completed. Only partial results are obtained which is sufficient for us to draw some conclusions. We are currently working on simulations with the smaller inner core \( r_{icb} = 0.1 \). However, no results are yet available for discussion.

\[ \text{Figure 1. Variation of the mean field strength with respect to the Rayleigh number } R_{th} \text{ in the reverse process.} \]

Variation of the mean magnetic field strength (the \textit{rms} of the magnetic field in the outer core) as the Rayleigh number decreases from 15000 to 2000 is plotted in Figure 1. From
the figure one can observe clearly an abrupt drop of the field strength: it decreases by more than 2 orders of magnitude from $R_{th} = 2420$ to $R_{th} = 2400$ (less than 1% in magnitude). This field reduction is also reflected in the force balance in the core. As shown in Figure 2, the ratio of the Lorentz force to the buoyancy force remains the same order for $R_{th} \geq 2420$. In other words, it is a strong-field dynamo right before the sudden drop at $R_{th} = 2400$. These numerical results suggest that a critical value exists between $R_{th} = 2400$ and $R_{th} = 2420$.

We also carried out a series of numerical simulations for the forward process starting from $R_{th} = 2000$. At this Rayleigh number, the numerical solutions show that the system is in purely thermal convection (i.e. any given small magnetic field perturbation decays exponentially in time). Initial results show that there is no dynamo solution for $R_{th} \leq 2500$. Strong field dynamo solutions are obtained for $R_{th} \geq 2700$. We are still working on the simulation to better allocate the critical Rayleigh number for the onset of the dynamo action. However, the results we have obtained by far suggest strongly that the strong-field dynamo is subcritical, since no dynamo solution has been found for $R_{th} \leq 2500$, larger than the critical value for the sudden termination of the strong-field dynamo in the reverse process.

Our numerical solutions suggest that during the sudden termination of the strong field dynamo, the field polarity also reverses, as shown in Figure 3. This polarity reversal deserves further study.

**Implications for Mars Magnetism:** The numerical simulation is still ongoing. More results for different parameters and core geometries will be obtained soon. These results are necessary to draw a complete picture for the implications for Mars dynamo and early evolution history.

![Figure 2: Ratio of the Lorentz force to the buoyancy force for the various Rayleigh numbers in the reverse process. In this plot, the spherically symmetric buoyancy force is included. However, this part does not affect dynamo process (it is balanced by the pressure gradient). The actual ratio of the Lorentz force and the effective buoyancy force is much larger, of order unity in the core.](image)

![Figure 3: The radial component $B_r$ of the magnetic field at the CMB for (a) $R_{th} = 6000$, (b) $R_{th} = 3000$, (c) $R_{th} = 2500$ and (d) $R_{th} = 2400$.](image)

If Mars dynamo is a sub-critical strong field dynamo, similar to the one obtained from our numerical simulation, then we conjecture that it could operate longer in the core, since the energy required to main the strong-field dynamo (once it is fully generated) is much lower than that for the onset of the dynamo (in this numerical simulation, the difference could be as large as 10% in magnitude). Also the rapid decrease in the field strength indicates that the termination of the dynamo action occurs on a very short period of time (less than 1% reduction of the driving force) compared to the evolution history of the Mars. The reversals of the field polarity during the dynamo termination could also affect the crustal magnetization in the final dynamo stages. It is very interesting to find whether further observations could help identify the properties of the dynamo action in the Mars core.