HOW DID THE MARS DYNAMO STOP: A DYNAMIC PERSPECTIVE ON THE FINAL STAGE OF THE MARS DYNAMO W. Jiang[1] and W. Kuang[2], [1]Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, jiangw@umbc.edu, [2]Planetary Geodynamics Laboratory, Goddard Space Flight Center, Greenbelt, MD 20771, Weijia.Kuang-1@nasa.gov,

Summary: Our previous numerical simulation [1] has shown that the Mars dynamo can be subcritical in its final stage. This implies that a very small perturbation to the buoyancy force (measured by the Rayleigh number) near the subcritical point could shut down the dynamo permanently. Further analysis shows that, the magnetic field and the dynamo mechanisms in the subcritical domain are significantly different from those in the super critical domain. While the time averaged mean field strength and the total dynamo region remain approximately constant, their variations are significantly larger in the subcritical dynamo domain. This suggests that as the Rayleigh number decreases, the total dynamo region remains low for longer periods. The dynamo action ends if the periods are sufficiently long such that the dynamo region is insufficient to support a global dynamo.

Introduction: Based on the magnetic measurement from the Mars Global Surveyor (MGS) mission [2], it is now accepted that Mars once had an active, strong-field dynamo in its early evolution history [3, 4]. But many other issues relating to the Mars dynamo are still under investigation. Among them is the energy budget for the Mars dynamo. Understanding of the energy budget shall provide not only the constraint for the duration of the dynamo action, but also insight on how the action is terminated.

Two sets of recent results have shed new insight on the termination of the Mars dynamo. One important result is from numerical simulation of the Mars dynamo [1]: the critical point (in terms of the buoyancy force driving the dynamo) for the dynamo annihilation can be lower than that for the onset of the dynamo [1]. This implies that the Mars dynamo can be subcritical in its last stage. Consequently, it can be terminated suddenly by a small reduction (less than 1%) to the buoyancy force in the Mars core. The other set of results is from the studies on giant impacts and the Mars remnant magnetic field [5]: from the remnant magnetization and the crater retention ages, the Mars dynamo may be terminated in a short period (less than 10 Ma) right after several giant impacts. In particular, these giant impacts could perturb (up to 2% of) the heat flow across the core-mantle boundary (CMB).

These two sets of results seem to support each other. But there are many uncertainties. For example, the parameters used in numerical simulation are very different from those appropriate for the Mars core. Thus the Mars dynamo may not be subcritical. The heat flow perturbation from the giant impacts may not necessarily imply to the reduction of the buoyancy force. The estimated termination period (~10 Ma) is very long for the Mars dynamo, approximately 4 orders of magnitude longer than the magnetic free decay time (~ 10,000 years) in the Mars core, etc. Therefore it is necessary to understand the properties of the magnetic field and of the dynamo action of the subcritical dynamo. It may provide additional information to help resolving the uncertainties on the termination of the Mars dynamo.

Numerical Simulation: The numerical model for the Mars dynamo simulation is the MoSST core dynamics model developed and modified in the past [6,7,8]. In this model, the Mars interior is divided into 4 regions, a solid inner core $r \le r_{\rm icb}$, a liquid outer core $r_{\rm icb} \le r \le r_{\rm cmb}$, a weak electrically conducting lower mantle $r_{\rm cmb} \le r \le r_{\rm dp}$, and an electrically insulating upper mantle $r_{\rm dp} \le r \le r_{\rm s}$. The mean radii ($r_{\rm icb}$, $r_{\rm cmb}$, $r_{\rm s}$) are chosen from the available estimations on the Mars interior. And the conducting lower mantle layer is assumed very thin (~ 50 km). The buoyancy force that drives dynamo is measured by the Rayleigh number R_{th} in the model.

With this specification and the parameters [1], we carried out two series of simulation experiments: one starts from a strong field dynamo at R_{th} = 15000. Then the experiments continue as R_{th} is reduced to 2400. In this process, the critical point for the termination of the dynamo is $R_{c1} \approx 2460$. The other set of simulation starts from R_{th} = 2400 at which there is no dynamo solution. As R_{th} increases gradually, we found the first dynamo solution at $R_{c2} \approx 2800$. Beyond this the solutions are similar to those obtained in the first series. The numerical simulation results indicate that the subcritical region is approximately $2460 \le R_{th} \le 2800$. Above $R_{th} \ge$ 2800, the Mars dynamo is supercritical.

To examine the differences between the two kinds of dynamo states, we focus on two physical quantities. The first is the (volume) mean magnetic field

$$|\mathbf{B}| = \left[\frac{1}{V}\oiiint_V |\mathbf{B}|^2 dV\right]^{1/2}. \qquad (1)$$

Its properties directly affect the magnetic field at the Mars surface, thus affecting the crustal magnetization. To analyze the dynamics of the dynamo states, we consider the following integral derived from the induction equation that describes the time variation of the magnetic field in the Mars core:

$$\frac{1}{2}\frac{\partial}{\partial t}\iiint_V \mathbf{B}^2 dV = \iiint_V \left[\mathbf{B}\cdot(\mathbf{B}\cdot\nabla)\mathbf{v} - \mathbf{j}^2\right] dV .$$

Then we divide the Mars core into the small regions V_+ in which the bracket in the second integration is positive (i.e. in the region the field strength grows in time) and the regions V_- in which it is negative (i.e. the field strength decreases with time). Then we introduce the concept of the dynamo volume

$$D \equiv \sum_V V_+ , \qquad (2)$$

and examine its properties as a function of the Rayleigh number. This quantity can be in particular illustrative for the dynamics: its magnitude and variation shall indicate whether and how a global dynamo state is sustained.

Results: The two quantities are evaluated for the dynamo states from R_{th} = 15000 (with a strong field dynamo state) down to R_{th} = 2480 (near the subcritical point). We focus on the time variations of |**B**| and D for a given Rayleigh number, and on their time averaged means and standard variations for different Rayleigh numbers. In Figure 1 are the time averaged mean and the standard variation of |**B**| for different Rayleigh numbers. As one can observe from the figure, the time averaged mean of |**B**| decreases with the Rayleigh num-

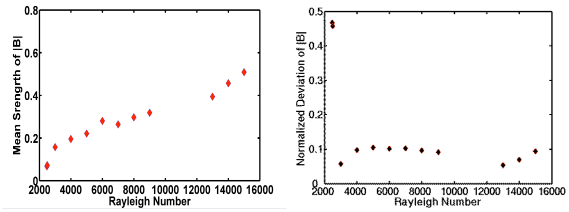

Figure 1 The time averaged mean (on the left) and the standard variation (scaled by the mean) (on the right) of |**B**| for various Rayleigh number R_{th}.

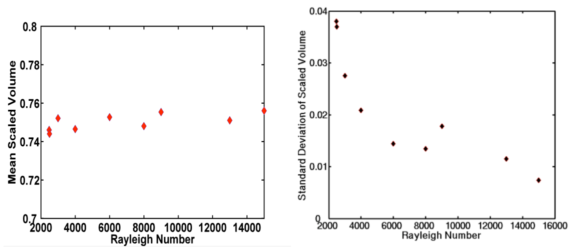

Figure 2. Similar to Figure 1, the time averaged mean (left) and the standard deviation (right) of the dynamo volume D for different Rayleigh numbers.

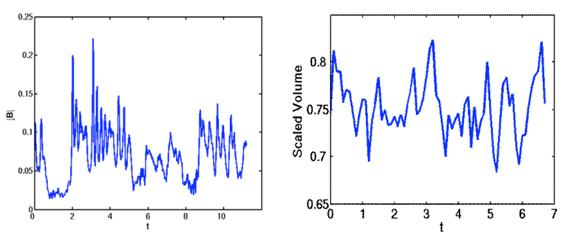

Figure 3. The time variation of |**B**| (left) and of D (right) at $R_{th} = 2480$. The time (horizontal axis) is scaled by the magnetic free decay time of the Mars core.

ber R_{th}. However, its standard variation increases significantly in the subcritical domain. The time variation of the dynamo volume D is very interesting: its time averaged mean is nearly constant through the entire Rayleigh number domain. However, its standard variation increases generally as the Rayleigh number decreases. In particular, the variation in the subcritical domain is significantly larger than those in the supercritical domain, as shown in Figure 2. The time variations of |**B**| and D at R_{th} = 2480 (near the subcritical point) are shown in Figure 3. From the figure one can observe that the variations cover a wide spectrum of frequencies. But the strongest modes are on the order one (the magnetic free decay time) time scales.

As defined in (2) the dynamo volume D is the summation of the all dynamo regions in the Mars core. These regions have very complicated spatial structures. In Figure 4 is a snapshot of the distribution of the dynamo regions (orange). To understand the dynamics, we plot in the figure also the anti-dynamo regions (blue) in which the magnetic field decreases in time. As one can observe, the dynamo and anti-dynamo regions interlace tightly with each other in the Mars core.

Discussion: The numerical results clearly demonstrate the distinct time variation patterns of the magnetic field strength |**B**| and the dynamo volume D in the subcritical and the supercritical domains: both |**B**| and D vary much more strongly in time as the Rayleigh number is reduced to the subcritical domain.

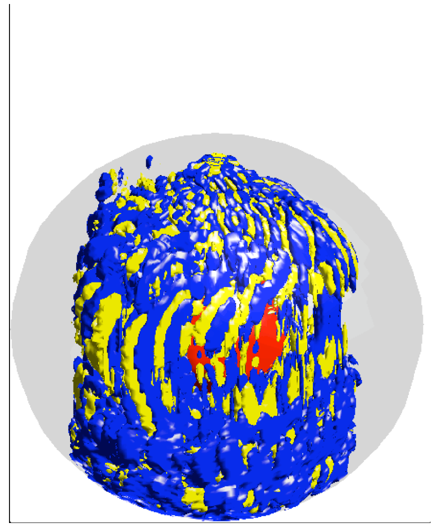

Figure 4 Snapshot of the isosurface of the dynamo regions (orange) and anti-dynamo regions (blue) in the Mars core at $R_{th} = 2480$.

From the results of D we may conjecture that there exists a critical dynamo volume limit D_c, below which the global dynamo state could not be sustained. In the subcritical dynamo domain, the dynamo volume D may cross the critical limit intermittently. The duration of staying below D_c increases as the Rayleigh number decreases. When the duration is sufficiently long, then the magnetic field will be sufficiently weak, so that a subcritical dynamo state could no longer be supported.

The time variation of |**B**| deserves also special attention. Since it varies strongly in the subcritical dynamo domain, we would expect that the field strength at the Mars surface shall also vary significantly. Consequently this will affect the crustal magnetization. If such effect is measurable, then it would provide additional observational evidence for a subcritical Mars dynamo.

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