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Subcritical dynamos in the early Mars' core: Implications for cessation of the past Martian dynamo

K. Hori [a,*], J. Wicht [b]

[a] Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[b] Max-Planck Institute for Solar System Research, Max-Planck-Strasse 2, Katlenburg-Lindau 37191, Germany

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ABSTRACT

Mars has no active dynamo action at present, but likely had one in the early stage of its history. Clarifying why and how it ceased is a challenging question. Several different scenarios have been proposed so far, here we explore the possibility that the dynamo stopped operating due to its subcritical nature. Former studies suggested that the subcritical regime is rather narrow, indicating that it may not play an important role for the cessation. Here we show that a more appropriate model for the early Martian dynamo, driven exclusively by secular cooling and using heat flux conditions at the outer boundary, yields a much wider subcritical regime than previously reported. This increased extent makes it more likely that subcriticality may have played a role in the shutdown of the early Martian dynamo. The magnetic field may thus have decayed rather quickly from its typical strength within a few thousand years after the heat flux through the core–mantle boundary became too low to support dynamo action. Because of the subcriticality, it would have been very difficult to restart the dynamo after the heat flux recovered, for example, after a major impact.

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1. Introduction

Mars Global Surveyor observed no global field but strong remanent magnetization in the Martian crust (e.g. Acuña et al., 1999; Langlais et al., 2004). This implies that Mars has no active dynamo action at present but likely had one in the past. This dynamo likely operated from the time of core formation until some time into the late heavy bombardment. Crater dating suggests that it ceased around 4 Ga ago (e.g. Lillis et al., 2008). This is supported by magnetic and textural studies of the oldest Martian meteorite ALH84001, which indicates a magnetization age of approximately 4 Ga (e.g. Weiss et al., 2008). An analysis of the crustal magnetization and crater ages of the largest impact basins on Mars suggested that the dynamo died in less than 0.02 Ga (Lillis et al., 2008) and thus rather quickly on a geological time scale.

Several scenarios have been proposed for how and why the ancient Martian dynamo died (see reviews by Stevenson, 2001; Breuer et al., 2010). Even today Mars may not have developed a solid inner core so that the early dynamo was purely driven by secular cooling. The dynamo would then have stopped operating once the heat flux through the core–mantle boundary (CMB) decreased below the adiabatic value (e.g. Stevenson et al., 1983; Williams and Nimmo, 2004; Breuer and Spohn, 2003). The heat flux can gradually decrease due to secular cooling or more abruptly when the style of mantle convection changes from plate tectonics to the rigid lid regime (Nimmo and Stevenson, 2000). Alternatively, giant impacts may also significantly change mantle convection (Roberts et al., 2009) and lead to a lower CMB heat flux or a less favorable CMB heat flux pattern. Giant impacts may also deposit enough heat into the core via shock waves to shut down the dynamo for several million years (Arkani-Hamed and Olson, 2010). However, since the last major impacts happened billions of years ago, the dynamo should have recovered from related effects.

Kuang et al. (2008) discussed the possibility of subcritical dynamo action for Mars. The presence of a strong magnetic field modifies the flow structure, mainly due to a balance between Lorentz and Coriolis forces. This modification can guarantee dynamo action at smaller Rayleigh numbers where a weak seed field may simply decay, i.e., it can lead to a subcritical situation. While the subcriticality cannot explain the cessation of the Martian dynamo by itself, it can help to understand why the dynamo did not recover after some temporary effects (impacts, CMB heat flux pattern) stopped it operating. Once the magnetic field has decreased, it cannot simply restart once the adverse circumstances are gone. As we will show below, the restart requires a much larger Rayleigh number, i.e., a significant increase in the CMB heat flux.

Subcriticality has been expected in convection-driven magnetohydrodynamic (MHD) dynamos since rotating magnetoconvection studies have shown that the presence of a magnetic field can

* Corresponding author. Tel.: +81 3 5841 5662; fax: +81 3 3812 9417.
E-mail address: khori@eri.u-tokyo.ac.jp (K. Hori).

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reduce the critical Rayleigh number for the onset of convection and can modify flow vigor and flow structures (e.g. Roberts, 1978, 1988, 2007 and references therein), although other mechanisms are also possible as proposed in cases of non-convection driven dynamos (Rincon et al., 2008). Fig. 1 illustrates the subcritical dynamo scenarios. Let us suppose that buoyancy forcing is increased, starting at a lower value when the heat transport is purely conductive. The forcing strength is quantified by the Rayleigh number Ra (a proper definition of Ra and the other parameters used in the following discussion will be given in Sections 2 and 3). Convection with a length scale $\mathcal{O}(E^{1/3}L)$ sets in when Ra reaches its critical value $Ra_c = \mathcal{O}(E^{-4/3})$ where the subscript 'c' stands for convection (e.g. Chandrasekhar, 1961; Busse, 1970; Jones et al., 2000). The Ekman number E measures the ratio of viscous to Coriolis forces and L is the characteristic length scale. Low Ekman numbers and thus strong Coriolis force promote a quasi two-dimensional geostrophic flow structure and inhibit convection. On further increasing Ra the flow amplitude grows until at Ra_d a magnetic Reynolds number Rm_d is reached that supports supercritical dynamo action that starts from a weak initial magnetic field (the subscript 'd' stands for dynamo action). The magnetic Reynolds number is a crucial parameter in dynamo action, measuring the ratio of magnetic field production to diffusion. As Ra is increased further, magnetic field and flow both intensify until the Lorentz forces are strong enough to significantly balance the Coriolis force and the dynamo jumps onto the strong field branch. The ratio of Lorentz to Coriolis forces is typically quantified via the Elsasser number Λ, which should be at least of order unity on the strong field branch, indicating that Lorentz forces contribute to the leading order force balance.

Once on the strong field branch dynamo action may be found for Rayleigh numbers smaller than Ra_d signifying subcritical dynamo activity. The Lorentz forces modify the flow to sustain dynamo action. The subcritical branch breaks down at Ra_d^{mag} once Rm decreases below the critical value Rm_d^{mag}. Critical magnetic Reynolds numbers Rm_d and Rm_d^{mag} generally differ since they measure the amplitude of flow structures differently modified by Lorentz forces. Magnetoconvection theory predicts that the presence of magnetic field leads to an increase of the flow length scale to $\mathcal{O}(L)$ and a

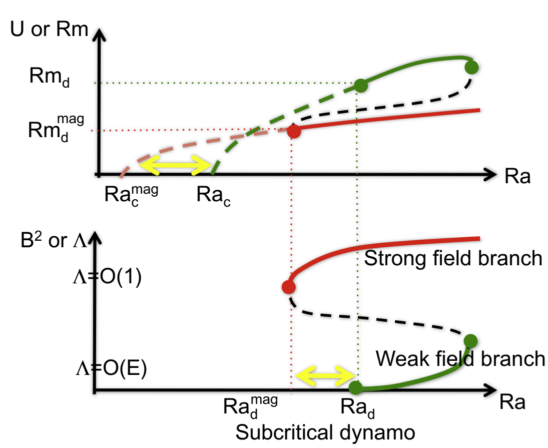

Fig. 1. A schematic diagram for subcritical dynamos. The horizontal axis is buoyancy forcing, or the Rayleigh number Ra. The vertical axis represents the flow vigor (top) or magnetic energy (bottom), corresponding to the magnetic Reynolds number Rm and the Elsasser number Λ, respectively. Green solid and dashed curves stand for a weak field branch and nonmagnetic convection, respectively. Red solid curves are for a strong field branch. A red dashed curve indicates an apparent magnetoconvection branch which is theoretically expected to be present when a strong field is imposed. Black dashed curves represent the unstable branch connecting the two branches. Yellow arrows indicate windows for subcritical dynamos (bottom) and convection (top). See the text for meaning of the labels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

decrease of the critical Rayleigh number to $Ra_d^{mag} = \mathcal{O}(E^{-1})$, indicating that the critical value for the corresponding dynamo action Ra_d^{mag} may also be lower than Ra_d. We measure the relative width of the window for subcritical dynamo action by $d_{sub} = (Ra_d - Ra_d^{mag})/Ra_d$. When the window becomes wide enough, dynamos subcritical even to the onset of nonmagnetic convection Ra_c may exist (e.g. Roberts, 1988, 2007). This has been found in Cartesian simulations at a low Ekman number of $E = \mathcal{O}(10^{-6})$ (Stellmach and Hansen, 2004), but never in full spherical shell MHD simulations (see Wicht et al., 2009 for an overview).

Morin and Dormy (2009) and Sreenivasan and Jones (2011) explored subcritical dynamo action in conventional spherical shell dynamo simulations, conventional in the sense that convection was predominantly driven by inner core growth and that fixed temperature boundary conditions were used. The subcritical window in these models turned out to be quite narrow with $d_{sub} < 0.2$. The range of magnetic Prandtl number for which subcriticality can occur is also limited (Morin and Dormy, 2009). The magnetic Prandtl number is the ratio of viscous to magnetic diffusivity. It is hard to predict whether such a narrow window would have major implications for the Martian dynamo.

In the following we will show that the subcritical window in a modified dynamo better adapted to model early Mars is much wider. We briefly introduce the model in Section 2 before presenting the numerical results in Section 3. The paper closes with a discussion in Section 4.

2. Model

We performed numerical MHD simulations for dynamos driven by three-dimensional Boussinesq convection in rotating spherical shells. The dimensionless governing equations for temperature T, velocity $\mathbf{u}$, non-hydrostatic pressure perturbation P and magnetic field $\mathbf{B}$ are as follows:

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \frac{1}{Pr}\nabla^2 T + S, \tag{1}$$

$$E\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -2\hat{\mathbf{e}}_z\times\mathbf{u} - \nabla P + Ra' T\frac{\mathbf{r}}{r_o} + E\nabla^2\mathbf{u} + \frac{1}{Pm}(\nabla\times\mathbf{B})\times\mathbf{B}, \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) + \frac{1}{Pm}\nabla^2\mathbf{B}, \tag{3}$$

$$\nabla\cdot\mathbf{u} = 0, \quad \nabla\cdot\mathbf{B} = 0. \tag{4}$$

We have chosen the shell thickness $D = r_o - r_i$ as a length scale, the viscous diffusion time D^2/ν as a time scale, $(\rho\mu_0\lambda\Omega)^{1/2}$ as a magnetic scale, and $D\beta$ as a temperature scale. Here r_i and r_o are the inner and outer core radii, respectively, ν is the kinematic viscosity, ρ the density, μ_0 the magnetic permeability, λ the magnetic diffusivity, Ω the rotation rate, and $\beta = -\partial T(r_o)/\partial r$ the radial temperature gradient at the outer boundary. The modified pressure P also accounts for centrifugal forces due to the system rotation rate Ω. The term S on the right hand side of Eq. (1) is a dimensionless homogeneous buoyancy source term. Non-dimensional control parameters are the Ekman number $E = \nu/(\Omega D^2)$, the Prandtl number $Pr = \nu/\kappa$, the magnetic Prandtl number $Pm = \nu/\lambda$, the modified Rayleigh number $Ra' = Ra\ E/Pr = \alpha g_o D^2\beta/(\nu\Omega)$, and the aspect ratio $\eta = r_i/r_o$, with κ being the thermal diffusivity, α the thermal expansivity, g_o the reference gravity at the outer boundary, and Ra the conventional Rayleigh number. We assume that gravity increases linearly with radius.

Thermal evolution models suggest that the early Martian dynamo probably operated without an inner core being present (see Section 1). The dynamo was thus exclusively driven by secular cooling and radiogenic heating, which can both be modeled by homogeneously distributed heat sources (Kutzner and Christensen,

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