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The influence of degree-1 mantle heterogeneity on the past dynamo of Mars

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ABSTRACT

The hemispheric dichotomy in the crustal magnetic field of Mars may indicate that the planet's past dynamo was influenced by a degree-1 heterogeneity on the outer boundary of its liquid metallic convecting core. Here we use numerical dynamos driven by purely volumetric internal heating with imposed degree-1 heat flux heterogeneities to study mantle control on the past dynamo of Mars. We quantify both south–north and east–west magnetic field dichotomies from time-average properties that are calculated according to two different end member crust formation scenarios. Our results indicate that a moderate heat flux anomaly may have been sufficient for obtaining the observed dichotomy. Because of the excitation of a strong equatorial upwelling in the dynamo, the efficiency of a mantle heterogeneity centered at the geographical pole in producing a south–north dichotomy is much higher than that of an heterogeneity centered at the equator in producing an east–west dichotomy. These results argue against a significant True Polar Wander event with major planet re-orientation after the cessation of the dynamo.

1. Introduction

The existence of an intrinsic magnetic field on Mars was debated until 1997, when the NASA mission Mars Global Surveyor (MGS) was inserted into orbit. At an altitude of 400 km, the Martian magnetic field components measured by MGS (Acuña et al., 2001) vary between ±250 nT, and at a lower altitude of 200 km they vary between ±650 nT. This drastic increase indicates a crustal nature to the Martian magnetic field, in contrast to Earth's anomalous crustal field which comes in excess or in deficit of the main core field. The only plausible cause for the crustal field is remanent magnetization acquired in the global field of a now extinct Martian dynamo. The largest anomalies are located south of the crustal topographic dichotomy. To first order, the northern plains, the largest volcanoes, and the largest impact craters are devoid of significant magnetic signatures.

Models that try to explain the dichotomy in the Martian crustal magnetic field fall into two categories, which we call here 'external' and 'internal'. In the external models, it is assumed that originally the entire Martian crust had been magnetized by a homogeneous internal dynamo. Later, when the dynamo had ceased to operate, parts of the magnetized crust were altered or removed by external processes such as large impacts or volcanic activity. For example, Milbury and Schubert (2010) assume that the original Martian crust had been magnetized by an internal dipole field, and that later the whole Northern hemisphere, the Tharsis volcanic province and several large impact basins are demagnetized. Their model is correlated with the Martian crustal field, but only at low spherical harmonic degrees, which contain little power. The correlation at degrees two and three requires a paleopole position at low- or mid-latitudes. While demagnetization of the crust in large impact basins seems plausible, a catastrophic event that demagnetized the entire Northern hemisphere seems less likely (Roberts and Zhong, 2006) although not impossible (Andrews-Hanna et al., 2008; Marinova et al., 2008; Nimmo et al., 2008). Large basin-forming impacts have also been invoked as cause for the sudden cessation of the paleo dynamo by reducing the core–mantle boundary (CMB) heat flux (Roberts et al., 2009) or by shock-heating the outer core leading to a stable thermal stratification (Arkani-Hamed and Olson, 2010).

The internal scenario for explaining the magnetic dichotomy assumes that the Martian crust was magnetized in a globally uneven way by a dynamo that was more active in the Southern hemisphere than in the Northern hemisphere. Even for homogeneous boundary conditions, hemispheric dynamos were found in numerical models (Grote and Busse, 2000; Simitev and Busse, 2005) for certain combinations of control parameters. In this case the selection of the magnetically active hemisphere is arbitrary and may flip in time. A degree-one thermal heterogeneity of the lower mantle could favor hemispheric dynamos in a broader range of control parameters and fix the magnetic activity to a preferred hemisphere (Stanley et al., 2008).

There are several possible causes for a hemispheric difference in the lower mantle. The intense volcanism in the region of Tharsis, together with strong gravity and topography signals there, suggest

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one-plume mantle convection upwelling below Tharsis (Zuber, 2001). Furthermore, experiments show that the Spinel to Perovskite transition may occur in the lowermost mantle of Mars (Fei et al., 1995). Harder and Christensen (1996) modeled mantle convection with such endothermic phase transition in the lowermost mantle and showed that one-plume convection emerges. Roberts and Zhong (2006) proposed that layered viscosity in the Martian mantle may lead to a degree-1 convection. Alternatively, a giant impact pre-dating the magnetization of the crust by a dynamo might have created the topographic dichotomy at the surface and set up a persistent degree one convection pattern in the mantle (Schubert et al., 2000).

Following the hypothesis of a degree-one mantle dichotomy, Stanley et al. (2008) imposed an inhomogeneous heat flux pattern with a component of spherical harmonic degree one and order zero (Y_1^0) on the outer boundary of their numerical dynamo simulation. The amplitude of the heat flux variation exceeded the mean, which means that in most of the Northern hemisphere the superadiabatic part of the CMB heat flux was assumed to be negative (inward). They found a strong south–north magnetic field dichotomy in snapshots of the magnetic field in their model. Remaining questions include:

- Can the observed dichotomy magnitude be obtained with a more moderate CMB heat flux anomaly?
- Can the dichotomy be recovered systematically in time-average field properties, corresponding to different crust formation scenarios?
- Since the mantle convection pattern was not necessarily axisymmetric with respect to the geographical pole, can a south–north dichotomy be produced if the axis of the mantle dichotomy is located at an arbitrary (e.g. mid-) latitude?

In this paper we address these issues by studying numerical dynamos driven by purely thermal convection with an imposed degree-1 heat flux heterogeneity on the outer boundary. We use heat flux anomalies of moderate amplitude corresponding to positive (outward) superadiabatic heat flux on the whole boundary. We examine Y_1^0 and Y_1^1 heat flux patterns and a combination of both. We calculate time-average field properties and their associated hemispheric dichotomies in north–south and east–west directions.

2. Current and past Martian magnetic field dichotomy

2.1. Current magnetic dichotomy

In order to quantify the degree of dichotomy of the Martian magnetic field we use the model by Langlais et al. (2004). At any given location above Mars' surface, the magnetic field is the sum of all Equivalent Source Dipole (ESD) contributions located within a certain distance. Using low- and high-altitude MGS measurements, a global map of the Martian magnetic field at altitude 400 km was produced. The horizontal resolution of the model is 170 km, or 2.9° at the equator.

Fig. 1 shows the model of the current Martian crustal magnetic field intensity B at a height of 400 km above the planet's surface (Langlais et al., 2004). According to this model, the rms of the current field intensity B in the Southern hemisphere is 29.5 nT, while the rms field in the Northern hemisphere is 8.4 nT, giving an hemispheric dichotomy ratio of 3.5. However, accounting for $\pm\sqrt{3}$ nT uncertainty in each hemisphere may give the range

$$B_{sh}/B_{nh} = 2.7 - 4.7 \qquad (1)$$

for the current magnetic field hemispheric dichotomy. When searching for an hypothetical geographical pole location that yields maximal dichotomy, we obtain a dichotomy factor of 3.55 at (150°E, 85°S). This ratio is only slightly larger than the actual value and the deviation from the geographical pole is only 5°, proving that the orientation of the current dichotomy is nearly perfectly south–north.

2.2. Crustal thickness dichotomy

The Martian crust is thicker in the Southern hemisphere than in the Northern hemisphere, which may possibly explain part of the magnetic dichotomy. The thickness of the magnetized crust is controlled by the depth of the Curie temperature, i.e. the depth at which magnetic minerals lose their magnetic remanence, with the total crustal thickness as an upper bound. The Curie depth depends on the mineralogy (phase and composition), the surface temperature and the temperature gradient at Noachian time when the Martian dynamo operated.

The Curie temperature is mineral-dependent. Typical values are about 325 °C for pyrrhotite, 580 °C for pure magnetite and 670 °C for pure hematite. The Martian magnetic mineralogy is very poorly constrained (Dunlop and Arkani-Hamed, 2005). Magnetite, however, is an appealing candidate, because it possesses both a high Curie temperature and a large magnetization saturation. It occurs on Earth in both continental and oceanic crust as a primary or secondary mineral (Langlais et al., 2010). On Mars, magnetite has been detected by Spirit, on the plains and in the Columbia Hills of Gusev crater, a ~150 km-diameter crater south of Apollinaris Patera (Morris et al., 2006).

Current surface temperatures at Mars' surface are well constrained, ranging about −100 to 0 °C with an average value of −63 °C. Past temperatures can be partially constrained through the minerals that formed during the Noachian. The presence of kaolinite as observed at the surface of Mars implies that surface temperatures were likely in the 0–30 °C interval (Ehlmann et al., 2009). This is also consistent with the formation of valley networks at Noachian times, which requires the sustainability of liquid water for relatively long time intervals (Boulay et al., 2010).

The temperature profile in the Martian crust during the Noachian can be estimated indirectly from the thickness of the elastic crust, assuming a given temperature at its base. To a first order, the depth of the elastic layer is determined by the 650 °C-isotherm, beneath which the crust cannot support stresses over long intervals. Williams et al. (2008) studied the admittance, a transfer function between topography and gravity, to infer the effective elastic thickness for various parts of the Tharsis complex. The oldest parts are associated with the lowest values of the elastic thickness. Namely, the topography of the Thaumasia Highlands reflects an elastic thickness of about 20 km at the time of loading. Other studies found very similar values for all the Noachian age structures (Zuber et al., 2000; McGovern et al., 2004). Grott et al. (2007) investigated the deformation associated with two fault systems in the southern Thaumasia region. They concluded that the thermal gradient was between 17 and 32 K/km during the late Noachian to early Hesperian period. Ruiz (2009) further assumed different crustal heat production rates and found temperature gradients varying between 14.5 and 18.0 K/km depending on the estimated past surface temperature during the Noachian. Another approach consists in estimating the temperature gradient from evolution models. Choblet and Sotin (2001) assumed a stagnant lid regime for Mars' thermal evolution and concluded that the temperature gradient rapidly decreased from 30 K/km after accretion down to 8 K/km after 500 My of evolution.

Here we make the following assumptions. Noachian temperatures were on average 0 °C. Single domain magnetite is the most likely magnetic carrier and implies a Curie temperature of 580 °C. The temperature gradient ranges between 15 and 30 K/km, which implies a depth to the Curie temperature between 20 and 40 km.