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Giant impacts, heterogeneous mantle heating and a past hemispheric dynamo on Mars

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The martian surface exhibits a strong dichotomy in elevation, crustal thickness and magnetization between the southern and northern hemispheres. A giant impact has been proposed as an explanation for the formation of the Northern Lowlands on Mars. Such an impact probably led to strong and deep mantle heating which may have had implications on the magnetic evolution of the planet. We model the effects of such an impact on the martian magnetic field by imposing an impact induced thermal heterogeneity, and the subsequent heat flux heterogeneity, on the martian core-mantle boundary (CMB). The CMB heat flux lateral variations as well as the reduction in the mean CMB heat flux are determined by the size and geographic location of the impactor. A polar impactor leads to a north–south hemispheric magnetic dichotomy that is stronger than an east–west dichotomy created by an equatorial impactor. The amplitude of the hemispheric magnetic dichotomy is mostly controlled by the horizontal Rayleigh number Ra_h which represents the vigor of the convection driven by the lateral variations of the CMB heat flux. We show that, for a given Ra_h, an impact induced CMB heat flux heterogeneity is more efficient than a synthetic degree-1 CMB heat flux heterogeneity in generating strong hemispheric magnetic dichotomies. Large Ra_h values are needed to get a dichotomy as strong as the observed one, favoring a reversing paleodynamo for Mars. Our results imply that an impactor radius of ~1000 km could have recorded the magnetic dichotomy observed in the martian crustal field only if very rapid post-impact magma cooling took place.

1. Introduction

Giant impacts have strongly influenced the internal structure and dynamics of the terrestrial planets during the primordial stages of their evolutions (Hartmann and Davis, 1975; Benz et al., 1988; Asphaug et al., 2006; Andrews-Hanna et al., 2008; Marinova et al., 2008; Nimmo et al., 2008; Jutzi and Asphaug, 2011). These events are plausible explanations for remarkable features of the solar system such as the small volume of Mercury's mantle relative to its core (Benz et al., 1988; Gladman and Coffey, 2009), the Earth–Moon system (Canup, 2004) and the topographic martian and lunar hemispheric dichotomies (Marinova et al., 2008; Nimmo et al., 2008; Jutzi and Asphaug, 2011). Giant impacts have also been invoked to explain the initiation or cessation of the dynamos of the terrestrial planets and moons (Roberts et al., 2009; Arkani-Hamed and Olson, 2010; Reese and Solomatov, 2010; Monteux et al., 2013; Monteux and Arkani-Hamed, 2014). In these models, the impactors' radii typically range between 100 and 1000 km. These impacts deliver a large amount of heat to the deep mantle, which is likely to strongly affect the efficiency of core cooling and in turn the dynamo activity. Although there is a higher probability that a giant impact will fall on low-latitudes of the planetary surface (Le Feuvre and Wieczorek, 2011), true polar wander events can ultimately place the resulting thermal anomaly at high-latitudes of the Core Mantle Boundary (CMB). Moreover, large impacts could be responsible for significant resurfacing and reset the magnetization of the pre-impact material (Langlais and Thébault, 2011; Lillis et al., 2013).

On Earth, the influence of lower mantle thermal heterogeneity on core magnetohydrodynamics has been extensively studied

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using numerical dynamos with imposed non-uniform outer boundary conditions. It has been shown that heterogeneous CMB heat flux causes a deviation from axisymmetry in the core flow (Aubert et al., 2007), in the time-average paleomagnetic field (Olson and Christensen, 2002) and in locations of intense magnetic flux patches on millennial time-scales (Bloxham, 2002; Amit et al., 2010). It may also explain the emergence of intense magnetic flux patches in the equatorial region (Amit and Choblet, 2012) and may even yield field locking (Gubbins et al., 2007; Willis et al., 2007). Heterogeneous CMB heat flux may also recover the lateral variations in the inner-core boundary seismic properties (Aubert et al., 2008; Amit and Choblet, 2009). Finally, reversal frequency and the trajectory of the paleomagnetic dipole axis during reversals may also be governed by the heterogeneous lower mantle (Glatzmaier et al., 1999; Kutzner and Christensen, 2004; Olson et al., 2010, 2013; Olson and Amit, 2014).

Heterogeneous mantle control has also been proposed to explain some features of planetary magnetic fields. Cao et al. (2014) found that high equatorial CMB heat flux breaks the core flow symmetry and produces north–south asymmetric magnetic fields which may explain the observed field of Mercury (Anderson et al., 2012). Stanley (2010) argued that temperature differences in the surrounding envelope of the convective zone of Saturn axisymmetrize its magnetic field. It has also been proposed that CMB heterogeneity may have controlled the shape of the current Martian magnetic field (Stanley et al., 2008). Mars is characterized by a striking magnetic field dichotomy, which is correlated with the topographic dichotomy. The Northern Lowlands are mostly devoid of significant magnetic fields. In contrast the southern highlands exhibit large and in some places intense magnetic field anomalies, up to 1500 nT at 90 km altitude as measured by Mars Global Surveyor (Acuña et al., 1998). This is two orders of magnitude larger than the crustal magnetic field on Earth. In terms of magnetized material, this suggests a thick (40 km) and intensely magnetized (up to 12 A/m) lithosphere to produce the observed magnetic field (Langlais et al., 2004), or any combination of a thinner lithosphere and a more intense magnetization (e.g., Parker, 2003).

The martian magnetic dichotomy can be explained using two end-members scenarios. In the external scenario, the dynamo was equally strong in both hemispheres, and the resulting magnetization was equally strong in both hemispheres. Then the magnetization of the northern hemisphere was removed or erased after the dynamo cessation, e.g., by a giant impact (Nimmo et al., 2008) or volcanic activity (Lillis et al., 2008). Alternatively a significant magnetization was never recorded in the northern hemisphere because surface conditions, lithological or alteration processes were different from those in the southern hemisphere (Rochette, 2006; Quesnel et al., 2009; Chassefière et al., 2013). In the internal scenario, the magnetization is strong only in the southern hemisphere because the dynamo was hemispheric to begin with (Langlais and Amit, 2008; Stanley et al., 2008; Amit et al., 2011).

Such an hemispheric dynamo could have been driven by CMB heat flux heterogeneity possibly caused by a very large-scale mantle convection pattern (Harder and Christensen, 1996; Zhong and Zuber, 2001; Elkins-Tanton et al., 2003, 2005; Ke and Solomatov, 2006; Roberts and Zhong, 2006) or by a giant impact (Roberts et al., 2009). In this study we propose a model for the magnetic field dichotomy in which the dynamo hemisphericity (internal origin) is related to a large impact (external origin). For that purpose, we model heterogeneous CMB heat flux resulting from giant impact heating and investigate its influence on the core dynamo by imposing it as a static, laterally-varying outer boundary condition on numerical dynamo models. In this approach, the CMB heat flux pattern and amplitude, as well as the reduction in the mean heat flux with respect to a reference pre-impact value, are determined by the impactor size, using a synthetic description of the impact heating zone. In Section 2 we describe our method. The results are presented in Section 3. Discussion, post-impact time evolution and applicability of our results to Mars are given in Section 4. Conclusions and possible planetary applications are highlighted in Section 5.

2. Method

2.1. Impact heating at the Core Mantle Boundary

Large impacts brought to Mars a formidable amount of energy that is a function of the impactor mass and velocity, the latter strongly depending on the impacted planet radius R. After a large collision on a Mars-size body, a significant fraction of this energy is deeply buried as heat within the mantle and leads to a local temperature increase ΔT_0 below the impact site. The size and the shape of the post-impact thermal anomaly depend on several parameters such as the size of the impactor, the impact velocity and angle, and the structure of the martian mantle. Increasing the size of the impactor leads to an increase of the heated volume while increasing the impact angle from 0 (head-on impact) to larger values (oblique impacts) reduces the maximal depth reached by the post-impact thermal anomaly (Pierazzo et al., 1997; Pierazzo and Melosh, 2000). Here for simplicity, we consider that the volume of the thermal anomaly only scales with the size of the impactor and we consider the case of a head-on impact. Hence, the post-impact thermal anomaly in our models is approximately uniform within a spherical volume (termed isobaric core) with radius R_{ic} that is 1 to 1.44 times larger than the radius of the impactor R_{imp} (Pierazzo et al., 1997; Senshu et al., 2002; Monteux et al., 2013).

On Mars, the impactor size invoked to explain the topographic dichotomy ranges between 320 and 1350 km (Marinova et al., 2008; Nimmo et al., 2008). This has to be compared to the size of the martian mantle. Based on solar tidal deformations, the martian core radius has been estimated between 1520 and 1840 km (Yoder et al., 2003). For simplicity, we assume a core radius of 1700 km, which implies a mantle thickness of about 1700 km. Hence, considering that $R_{ic} = 1.44 R_{imp}$, the post-impact spherical thermal anomaly is likely to overlap the CMB for $R_{imp} > 500$ km. For an impactor radius of $R_{imp} = 1200$ km, the disruption of the impacted planet will only occur when the impact velocity reaches values of $\sim$100 km/s which is much larger than the impact velocity v_{imp} considered here ($v_{imp} = 5$ km/s) (Tonks and Melosh, 1992; Reese et al., 2010). In our models, we consider that the impactor radius ranges between 600 and 1000 km bearing in mind that larger impactors with larger impact angles could have similar thermal consequences at the CMB (Pierazzo et al., 1997; Pierazzo and Melosh, 2000).

As the volume of the isobaric core is governed by the size of the impactor, the magnitude of the temperature increase can be directly related to the impact velocity. Making the conservative hypothesis that the impact velocity is close to the martian escape velocity and that the volume of the isothermal sphere is 3 times larger than the impactor (Senshu et al., 2002; Monteux et al., 2013), the energy balance accounting for heating and melting of both the impactor and impacted material may lead to a uniform spherical temperature increase of $\sim$400 K in the martian mantle (Monteux et al., 2013). Away from the isothermal sphere, the temperature decreases rapidly with distance r as $(R_{ic}/r)^m$ with m typically ranging between 4 and 5 (Senshu et al., 2002; Monteux et al., 2007).

Geochemical evidence and crater densities indicate that the martian topographic dichotomy could have formed within the first 50 Myr of Solar System formation and that the martian northern