The effect of giant impactors on the magnetic field energy of an early Martian dynamo

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Introduction

Of all the planets in our solar system, only Mars and Venus currently have no active magnetic field. Mars is interesting because we know that there was once a strong magnetic field due to the observed remanent magnetisation locked in the planets crust (Figure 1) [1].

Similar timing for the estimated cessation of the magnetic field (~4Ga) and the Late Heavy Bombardment (3.7-4.1Ga) have lead to theories that a single, or multiple, giant impacts could have killed the Martian dynamo through mantle heating and a decrease in the average CMB heat flow [2,3,4].

Previous studies have investigated this theory but do not take into account the initial shock heating that causes an increase in average heat flux [3,5,6]. Here, we chose six time points with a varying average heat flux and heat flux heterogeneity size to show that the time-averaged magnetic field energy decreases to below pre-impact values.

Remanent magnetisation of Mars

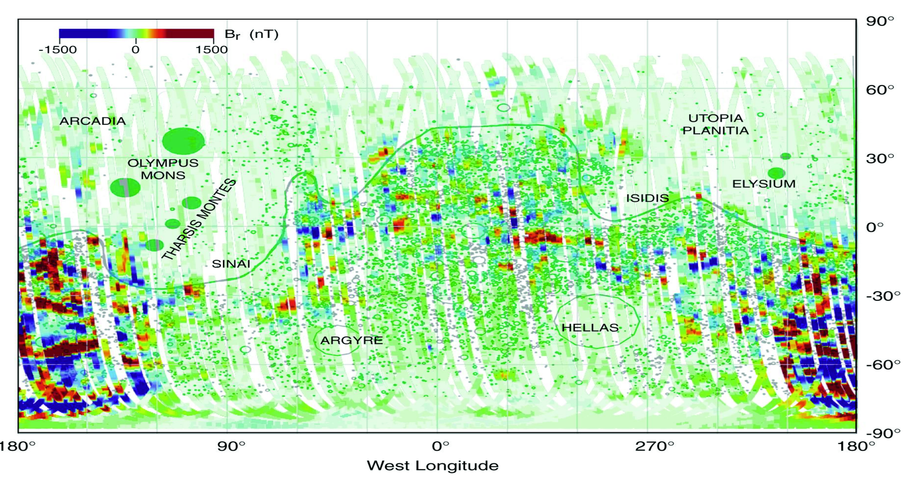

Figure 1. Remanent magnetisation measured at an altitude of <200km [1]. The solid green line illustrates the north-south dichotomy boundary separating the magnetised southern uplands and the low-magnetised northern lowlands. It is important to note the lack of magnetisation in the following basins; Hellas, Argyre, Isidis and Utopia.

Methods

Impact model results were used from the study by Julien Monteux and Arkani-Hamed [7]. Their outputs are in the form of a 2D temperature field from 0-22Myrs after impact for an impactor of diameter 750km. The data was transformed to find the heat flux at the CMB, shown below for six chosen post-impact time points.

CMB heat flux patterns used as boundary conditions for an equatorial impact

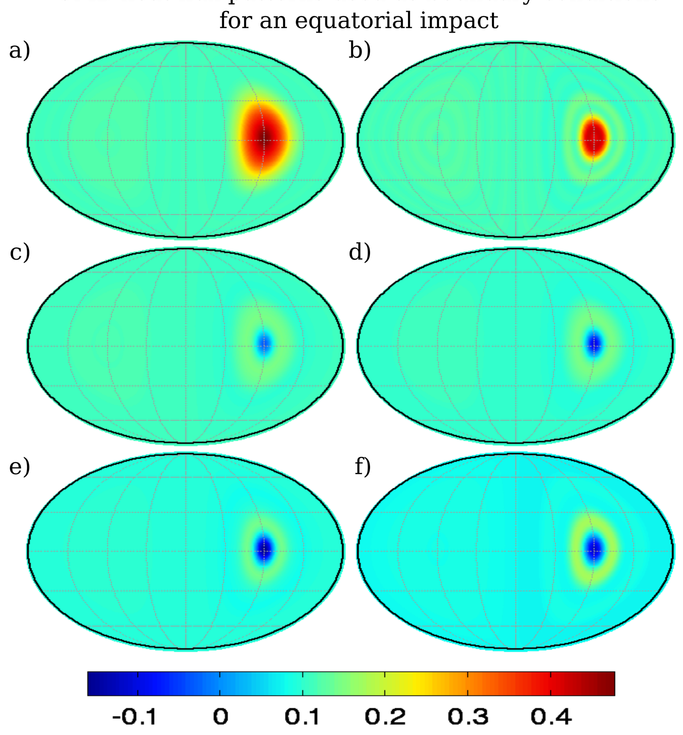

Figure 2. The heat flux patterns at the Martian CMB for time (a) 10yrs, (b) 221kyrs, (c) 797kyrs, (d) 1.99Myrs, (e) 5.06Myrs and (f) 20.21Myrs. The size and amplitude of the heat flux anomaly depends on the impactor diameter. (a) The initial increase in localized heat flux out of the core is a result of the initial shock heating directly below the CMB layer. (b-c) The direction of heat flux reverses rapidly due mantle heating caused by the hot, sinking impactor core. The examples shown are with respect to an equatorial impact.

Heat flux patterns are decomposed into spherical harmonic coefficients in order to be implemented as boundary conditions in the numerical model. The dynamo code PARODY-JA was used [8].

The variation of total heat flux at the CMB, Q, also varies the canonical Rayleigh number, Ra_c, with the follow relation where Ra_c is used as a time stepped control parameter for the dynamo model:

$$Ra_c = Ra_Q Pr^2 E^{-3} \text{ where, } Ra_Q = \frac{\alpha g_0 Q}{4\pi C_p \Omega^3 D^4}$$

The evolution of the Rayleigh number is shown in Figure 3 along with the heat flux anomaly properties and its effect on the CMB heat flux.

Heat flux heterogeneity and control parameter inputs

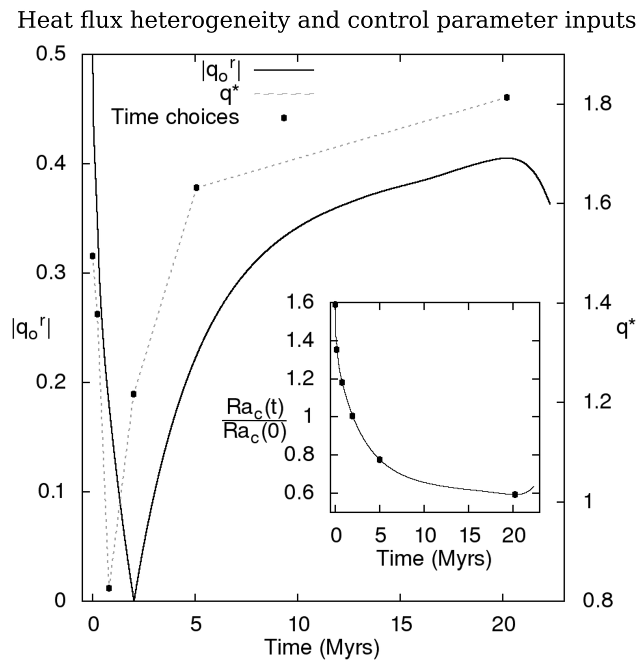

Figure 3. Shown is the magnitude of reduction in the mean CMB heat flux, $|q_0^r|$, caused by the impact along with the amplitude of the heat flux anomaly, q*. Due to the initial shock heating the average heat flux increases resulting in the negative gradient for $|q_0^r|$. After ~2Myrs the gradient reverses showing that the average heat flux is now lower than the pre-impact value. The trend for q* also conforms to this such that there is a transistion from strong outward heat flow to an inward heat flow. The inset shows the evolution of the Rayleigh number. The points in both plots show the time step choices related to the above heat flux patterns (Figure 2) and the implemented Rayleigh number relative to the initial value.

Results

Three sets of models were simulated:
1 - Polar impact with varying Rayleigh number,
2 - Equatorial impact with varying Rayleigh number,
3 - Homogeneous heat flux with varying Rayleigh number.

Initial simulations show that the time-averaged magnetic field energy decreases below the pre-impact value after a few of the chosen time steps (Figure 4a).

The initial simulations only lowered the time-averaged energy where the aim is to kill the dynamo. To do this, a new pre-impact model was brought closer to convection onset by lowering the Rayleigh number.

Furthermore, we lowered the Ekman number closer to planetary values and ran the simulations longer to increase the accuracy of the time-averaged energy.

These simulations are currently on-going but initial results (Figure 4b) for the first two chosen time points show similar unexpected behaviour as the initial simulations which did eventually lead to a general decrease in dynamo action (Figure 4a).

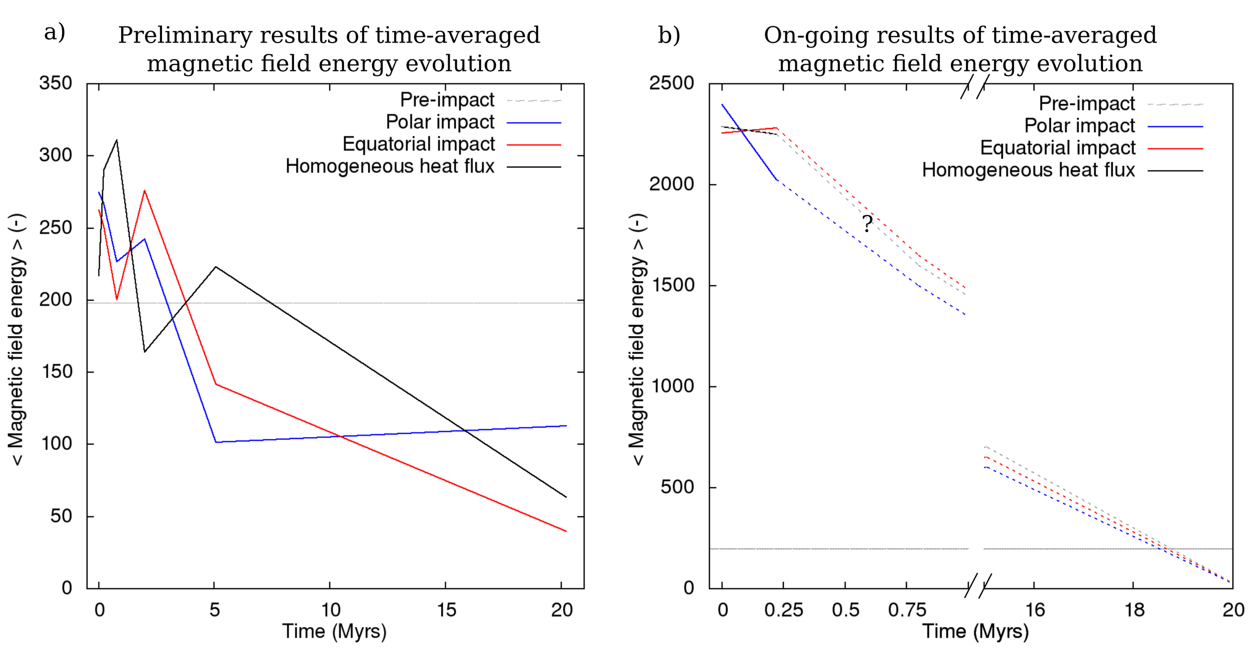

Figure 4. (a) Time-averaged magnetic field energy results for the initial simulations. The trend shows that for all models the time-averaged field energy decreases below the pre-impact value. An increase in time-averaged energy is seen directly after impact due to the shock heating. (b) Time-averaged magnetic field energy results for the on-going simulations. Although it might be too soon to predict the behaviour based on only the first two time points, similar unexpected behaviour has been seen in (a) which did eventually lead to a general decrease in magnetic field energy.

Dynamical magnetic fieldline imaging (DMFI) algorithm [8] is used to show the magnetic field lines (displayed in grey) inside the core.

A snapshot of the pre-impact model and post-impact models are shown below to illustrate the increase in number and strength of the field lines due to the impact.

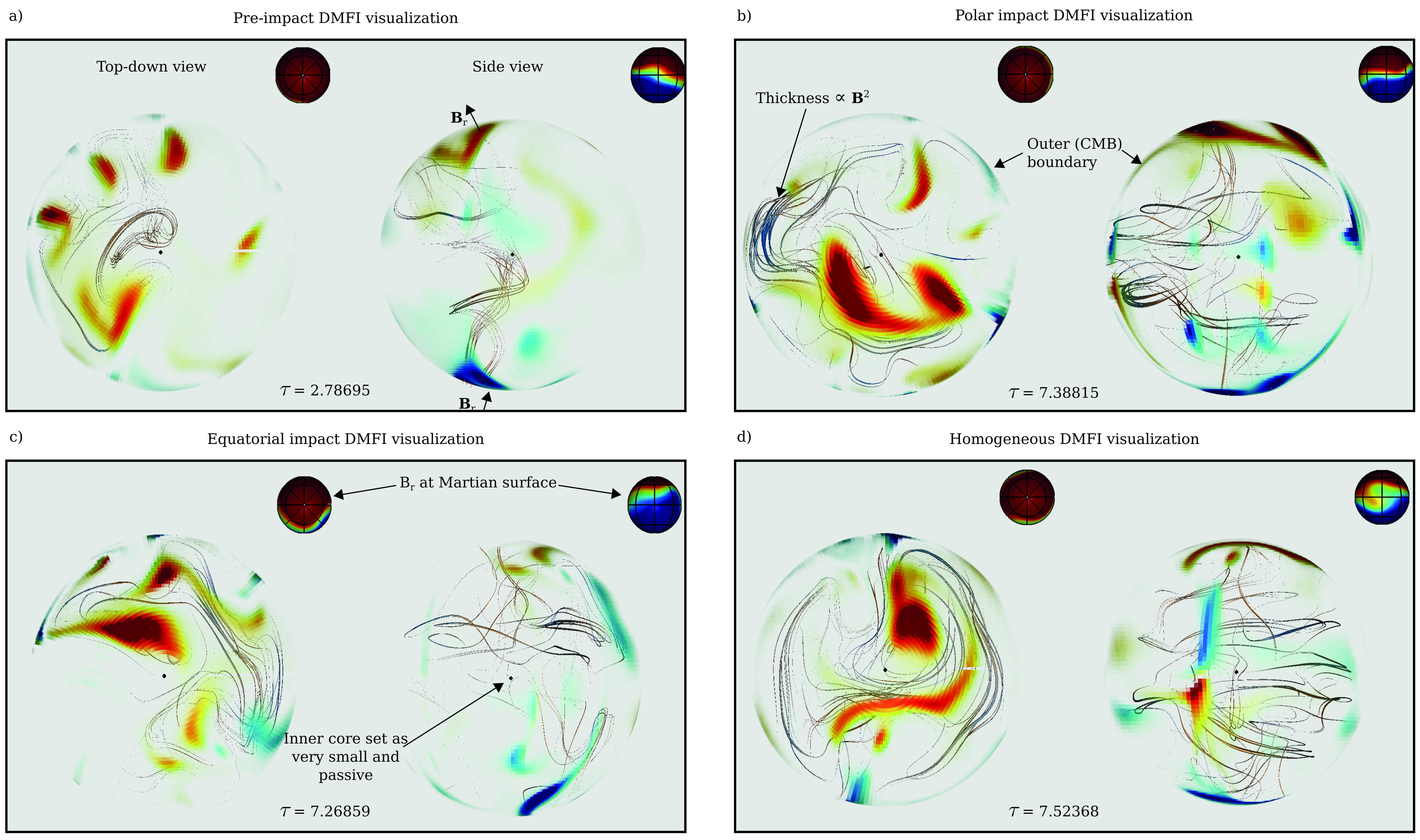

Figure 5. Snapshots at magnetic diffusivity time, τ, where similar post-impact times are chosen for consistency. The left-hand panel shows the top-down view and right-hand panel shows the side view. The red patches represent outward radial magnetic field and blue patches inward. Field line thickness is proportional to $\mathbf{B}^2$ and the outer boundary is made selectively transparent using a transparency level that is inversely proportional to the local radial magnetic field. The insets located top-right show the radial magnetic field on the Martian surface and are used to monitor the large-scale orientation and strength of the magnetic dipole [8].

Conclusions

- An impactor of diameter 750km would have caused disruption to the early Martian dynamo.
- We have shown that before the core begins to recover from the impact, the time-averaged magnetic field energy has decreased to below pre-impact values.
- Initial results for the on-going simulations follow the same trend where the expected result should kill the dynamo and decrease the magnetic field energy to zero.
- These results add weight to the theory that giant impacts were the cause for the cessation of the Martian dynamo.

Further research

- Two new sets will be simulated which will determine the effect of only the heat flux heterogeneities on the dynamo:

  1 - Polar impact with fixed Rayleigh number,

  2 - Equatorial impact with fixed Rayleigh number.

- Potential extra investigations could include:

  1 - Can the dynamo be restarted by increasing the Rayleigh number back to pre-impact values?

  2 - If the heterogeneity alone has a small effect on the dynamo, what size and amplitude is required to kill it?

  3 - Simulate the effects of multiple impact events or impact locations at various latitudes.

References

[1] Acuña et al., (1999). Science, 284:790-793.
[2] Chapman et al., (2007). Icarus, 486:233-245.
[3] Roberts et al., (2009). Journal of Geophysical Research, 114:E04009.
[4] Kuang et al., (2014). Geophysical Research Letters, 41:8006-8012.
[5] Sreenivasan and Jellinek, (2012). Earth and Planetary Science Letters, 349-350:209-217.
[6] Amit et al., (2011). Physics of the Earth and Planetary Interiors, 189:63-79.
[7] Monteux and Arkani-Hamed, (2014). Journal of Geophysical Research: Planets, 119:480-505.
[8] Aubert et al., (2008). Geophysical Journal International, 172:945-956.

Further information

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