DELAYED ACTIVATION OF MARTIAN CORE DYNAMO.

J Arkani-Hamed (Department of Physics, University of Toronto, Toronto, ON, Canada, M5S 1A7, jafar@physics.utoronto.ca)

Introduction: There are evidence that the core dynamo of Mars ceased at around 4 Ga [1]. But when the core dynamo actually started is an outstanding issue. The present study indicates that there was no appreciable core dynamo within the first 50-120 Myr of Mars history, and a strong dynamo was active for only ~300 Myr. The delayed activation of the core dynamo is related to the high-velocity embryo-embryo collision likely occurred in the very last stage of the planetary formation. The impact heating of the core thermally stratified the core, which prevented the global core convection and generation of the core dynamo immediately after the accretion.

Impact Heating of Mars Embryo: The thermal evolution models of a growing martian embryo suggest that a thick magma ocean and an iron core were likely developed before Mars completed its accretion [2]. Here I consider the very last embryo-embryo collision when the Mars embryo has already reached almost the present size. Impacting embryo sizes of 1000 and 1500 km in diameter are examined.

Figure 1 shows the impact induced temperature increase in Mars embryo caused by the small 1000 km impacting embryo, calculated using the foundering model of Watters et al. [3]. The collision increases the temperature of Mars embryo by over 3500 K inside the isobaric zone of about 750 km in diameter, outside which the temperature decreases exponentially. The large 1500 km embryo produces a larger isobaric zone.

The molten iron produced by the impact heating of planetesimals during Mars embryo growth is thermally in equilibrium with the partially molten magma ocean whereas, the embryo-embryo collision involves a large body colliding with martian embryo at much higher velocities of ~10 km/s, which delivers a significant amount of energy and raises the temperature of the impact site by a few thousand degrees.

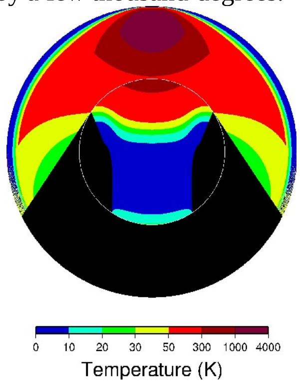


Figure 1

Post-Impact Cooling of the Core: The temperature of the pre-impact iron core depends on the temperature of the iron differentiated from the magma ocean and the descent mechanism of iron blobs. The pre-impact temperature of the core is assumed spherically symmetric and adiabatically increasing with depth starting at 2200 K at the core-mantle boundary.

The iron content of the impacting embryo melts and sinks to the core-mantle boundary. The temperature of the isobaric zone, ~3500 K, implies that the superheated iron of the embryo can be ~2000 K hotter than the core of Mars. Due to the positive buoyancy of the superheated embryo iron relative to the iron core of Mars, the embryo iron spreads on the core and creates a superheated iron layer [4]. Two values for the temperature of the super-heated iron layer are examined, 1000 K and 2000 K hotter than the pre-impact core.

Figure 1 shows that the impact induced shock wave heats the core differentially. About 20% of the core-mantle boundary receives direct shock wave. The heterogeneous impact temperature in the core is no longer stable and causes thermal wave in the core which places the colder parts near the center and hotter parts near the core-mantle boundary, resulting in a stably stratified core with temperature increasing radially [5]. The stratification quenches the convection and kills the pre-existing core dynamo within a few hundred years.

The thermal evolution models of the core start immediately after the core stratification and formation of the iron layer. The convection starts inside a thin layer near the core-mantle boundary. While the outer core transfers major part of the heat to the mantle, some heat diffuses downward and further enhances the thermal stability of the deeper parts.

Figure 2 shows the thickness of the convecting layer versus time. The thickness increases gradually until it surpasses ~500 km, then increases very rapidly because the lower parts of the core have a temperature close to the adiabatic temperature, thus ready to convect. This depth threshold is about 1200 km for the large impacting embryo. The bottom boundary of the convecting layer reaches a radius of 300 km and the layer no longer deepens, because a conducting solid sphere of 300 km radius is artificially imposed at the center of the core to avoid singularity in calculating the magnetic field inside the convecting core.

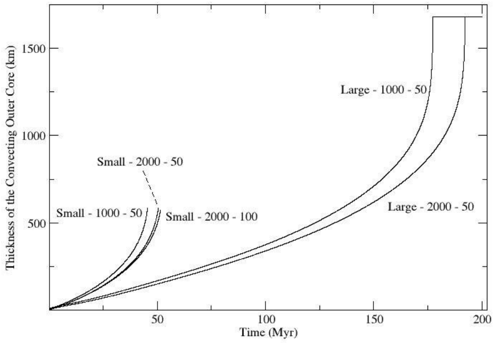
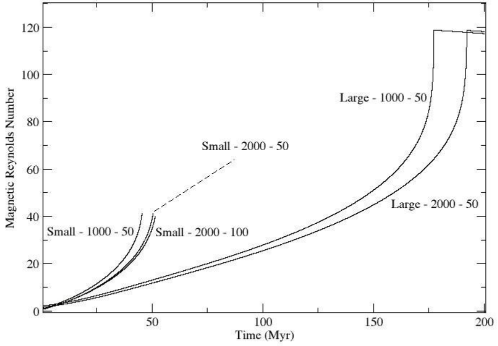


Figure 2. The first numbers on the curves denote the excess temperature of the iron layer and the second are the thickness of the overlying thermal boundary layer of the mantle. Similar for Figures 3 and 4.

The Delayed Core Dynamo Activation: A stably stratified core cannot support thermal convection and thus cannot power a thermally-driven core dynamo. However, the convecting outer core with high electrical conductivity is capable of generating a dynamo.



Figures 3

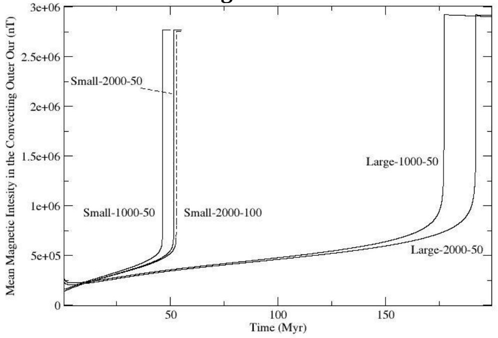


Figure 4

Figure 3 shows the time variations of the magnetic Reynolds number, indicating that the small impacting embryo delays the generation of self-sustained dynamo for about 50 Myr, whereas the large embryo impact prevents dynamo generation for about 120 Myr.

Figure 4 shows the time variations of the mean magnetic field intensity inside the convecting outer core determined using the scaling equation of Christensen and Aubert [6]. The intensity increases gradually until the convecting outer core thickness surpasses ~500 km (~1200 km for the large impacting embryo), then increases sharply reaching ~ 2.8 x10^6 nT when the entire core convects vigorously and the Reynolds number exceeds the threshold of ~40. The dipole magnetic field intensity at the core-mantle boundary can be 3-10 times weaker than the mean field intensity and by the time the dipole field reaches the surface of Mars it further decays by a factor of ~0.13. Therefore, the dipole field at the surface expected to magnetize the magnetic bodies of martian crust can be ~23,000 – 77,000 nT when the entire core vigorously convects, comparable to the present dipole magnetic field on the Earth.

It is clear from the figures that the most effective parameter is the size of the impacting embryo. Also, like the thickness of the outer convecting layer, both the Reynolds number and the magnetic field intensity are less sensitive to the temperature of the super-heated iron layer.

It is therefore quite possible that there was no strong core dynamo within the first 50-120 Myr of Mars history, i.e. since the very last embryo-embryo collision event. The primordial crust of South Province, south of 30S and ranging in longitude from west of Hellas basin to east of Argyre basin, is very weakly magnetic. There are a total of 9 craters of diameters larger than 200 km which have been produced after the formation of the crust. Each of the impacts that created the craters is capable of demagnetizing the entire crust of 60 km thickness and creating appreciable magnetic anomaly at satellite altitudes of ~400 km in case the crust was significantly magnetized prior to the impact, however, no appreciable magnetic anomaly were observed by Mars Global Surveyor over the craters [7]. This implies that the initially hot primordial crust has cooled below the magnetic blocking temperatures of its magnetic minerals in the absence of a strong core field. The entire crust could have taken ~100 Myr to cool through the magnetic blocking temperature range of magnetite, 570-580C, probably the main magnetic mineral of the martian crust, and could have acquired appreciable thermo-remanant magnetization if a strong core field existed.

References: [1] Lillis R. J., Frey H. V. and Manga M. (2008) GRL, 35,338. [2] Senshu H., Kuramoto K. and Matsui T. (2002) JGR,107, E12, 5118. [3] Watters W.A., Zuber M.T. and Hager B.H. (2009) JGR, 114, E0200. [4] Monteux J., Jellinek M. and Johnson C. L. (2011) LPSC, XXXII, Abstract # 1665. [5] Arkani-Hamed J. and Olson P. (2010b), GRL, 37, L02201. [6] Christensen U. R. and Aubert J. (2006), GJI, 166, 97–114. [7] Arkani-Hamed and Boutin (2012) Icarus, 217, 209–230.