EPSC Abstracts
Vol. 6, EPSC-DPS2011-1020, 2011
EPSC-DPS Joint Meeting 2011

An impact driven dynamo for the early Moon

M. Le Bars (1), M. A. Wieczorek (2), Ö. Karatekin (3), D. Cébron (1) and M. Laneuville (2)
(1) IRPHE, CNRS/Universités Aix-Marseille, France (lebars@irphe.univ-mrs.fr), (2) Institut de Physique du Globe de Paris, Univ Paris Diderot, France, (3) Royal Observatory of Belgium, Brussels, Belgium

Abstract

The origin of lunar magnetic anomalies remains unresolved after their discovery more than four decades ago. Several of these anomalies are associated with Nectarian-aged impact basins, and these signatures are the result of an impact melt sheet that was magnetized in the presence of a stable magnetic field over several thousands of years. The impact events that formed each of these basins were energetic enough to have unlocked the Moon from synchronous rotation, and the subsequent dissipation at the core-mantle boundary, combined with large-scale fluid flows in the core excited by tidal instabilities, could have powered a lunar dynamo at the time their impact melt sheets were cooling through the Curie temperature. Predicted surface magnetic field strengths are on the order of several μT, consistent with paleomagnetic measurements.

1. Introduction

Magnetic field measurements from orbit about the Moon have shown that portions of the lunar crust are strongly magnetized, and paleomagnetic analyses of lunar rocks show that some possess a stable remanent magnetization [1]. Nevertheless, after more than 40 years of analysis, the origin of the magnetic fields that magnetized the lunar crust are still debated [2]. One hypothesis posits that the Moon once possessed a thermally driven core dynamo, but this theory is problematical given the small size of the lunar core and the inferred surface field strengths. Another hypothesis is that impact events could have either generated or amplified pre-existing fields, most notably near the antipodes of the largest basins [3]. Two observations lead us to propose a different model for the generation of a global long-lived magnetic field. First, six Nectarian aged impact basins have central magnetic anomalies [4] that are most likely a result of their impact melt sheets having acquired a thermoremanent magnetization as they cooled though the Curie temperature of metallic iron. Given the slow conductive cooling timescales of these thick deposits, a stable magnetic field is required to have been present for thousands of years following the impact event. Second, each of these impact basins would have significantly affected the rotational state of the Moon. These events could have either unlocked the Moon from synchronous rotation, and/or set up large amplitude librations that would have lasted for several 10s of thousands of years [5]. Here, we propose an alternative mechanism for generating a lunar dynamo, where the energy for dynamo action comes from the rotation of the Moon rather than from thermal effects.

2. Tidal instability

A huge amount of energy is stored in the spin and orbital motions of any planet, and the question is to know how it can be efficiently transmitted to drive dynamo-capable core flows. Malkus [6] proposed that inertial instabilities, coming from a parametric resonance between two inertial waves of the rotating flow and a large scale natural forcing (such as precession or tides), could be this efficient conveyer. We have performed a systematic study of the tide driven instability in a deformable rotating fluid sphere [7]. A fully three-dimensional turbulent flow is excited as soon as the ratio between the ellipticity of the distorted boundary β and the square root of the Ekman number E is larger than a critical value of order one. The typical root mean square velocity of the flow is then of the order of magnitude of the differential rotation between the fluid and the tidal deformation. The dynamo ability of the tidal instability has yet to be explicitly demonstrated. Nevertheless, since it gives rise to flows similar to flows set up in the core by solid body precession, which are known to be dynamo capable [8], we are fully confident in considering this tidal instability as dynamo capable using a similar threshold. The typical amplitude of the generated magnetic field intensity in the core can then be evaluated by adapting the works of Christensen and co-workers [9, 10] to our case of mechanical forcing, by supposing that the field strength is controlled by the available mechanical power rather than by any force balance.

3. Results.

A standard three-layer model of the Moon in hydrostatic equilibrium predicts the core-mantle boundary ellipticity β to be between about 1.9×10^{-5} and 1.5×10^{-4}, depending on the distance between the Earth and Moon. Given that the lithosphere of the Moon is not in hydrostatic equilibrium, we also consider an ellipticity up to 10 times larger than the purely hydrostatic value. Assuming synchronous rotation of the Moon, we find an Ekman number ranging between 3.0×10^{-12} today and 10^{-12} in the past. This implies that a tidally driven instability in the lunar core could have been excited over its entire history. To excite this instability, an instantaneous non-zero differential rotation between the tidal deformation and the rotating fluid needs to be imposed, and we envision this differential rotation being an impulsive change in the rotation of the lunar mantle following a basin forming impact. Given the relatively short resynchronization timescales, the pre-impact tidal deformation of the core-mantle boundary would remain frozen into the mantle, thus providing a differential rotation between the fluid core and core-mantle boundary ellipticity. In order to achieve dynamo generation, two additional criteria must be met: (i) the time it takes for the tidal instability to establish a fully turbulent state must be shorter than the time it takes the core to spin up or down to the mantle rotation rate, and (ii) the core flow must be sufficiently vigorous so that the magnetic Reynolds number is larger than the threshold value for dynamo action. The expected magnetic field strength at the surface of the Moon is shown in Fig. 1. Note that the core-mantle boundary ellipticity does not affect the amplitude of the generated magnetic field, but it does influence the growth rates of the tidal instability, and hence the parameter space where it can develop. Dynamo action driven by tidal instabilities is possible over a large range of post-impact periods and Earth-Moon separations. Predicted magnetic field strengths are significant, from about 0.2 to 4 μT at the surface of the Moon following the formation of a 700 km diameter basin. These values compare favourably to those obtained from lunar paleomagnetic analyses that imply field strengths of ~1 μT [11]. Based on the core spin-up times, the duration for each impact induced dynamo is predicted to lie between about 2×10^3 and 8×10^3 years. This would allow about 1 km of impact melt to cool through its Curie temperature and acquire a thermoremanent magnetization.

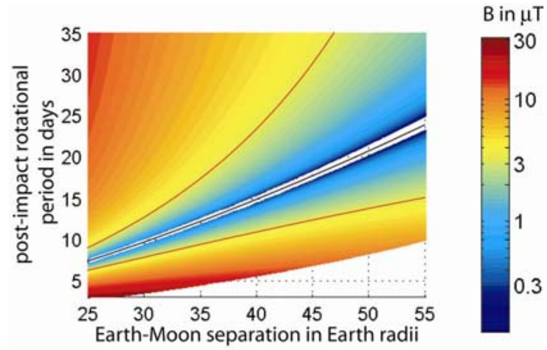

Fig. 1. Estimated magnetic field strength at the surface of the Moon. Field strengths are plotted only when dynamo generation is possible. Also shown is the synchronous rotation rate of the Moon (black line), and the expected range of rotational periods following the formation of a 700 km diameter basin by a 5 km s^{-1} impact with average impact conditions (red lines). The core-mantle boundary ellipticity is assumed to be equal to 10 times that of a purely hydrostatic Moon.

4. Conclusion

Dynamos powered by impact-induced changes in rotation rate and subsequent tidal instabilities could explain a large portion of lunar magnetic anomalies and sample natural remanent magnetizations. Similar time-variable tidal deformations on Mercury, Ganymede, (early) Earth, and other exoplanetary systems could potentially account for various aspects of the magnetic fields observed with these bodies.

References

[1] Fuller M. and Cisowski S. (1987), Geomagnetism, J Jacobs (ed.), 307-455, Academic Press, New York [2] Wieczorek M.A. et al. (2006), Rev. Mineral. Geochem., 60, 221-364. [3] Hood L. and Artemieva N. (2008), Icarus, 193, 485-502. [4] Halekas J. et al. (2003), Meteorit. Planet. Sci.,38, 565-578. [5] Wieczorek M.A. and Lefeuvre M. (2009) Icarus, 200, 358-366. [6] Malkus W.V.R. (1968) Science, 160, 259-264. [7] Le Bars M. et al. (2010) PEPI, 178, 48-55. [8] Tilgner A. (2005) Phys. Fluids, 17, 034104. [9] Christensen U.R. and Tilgner A. (2004) Nature, 429, 169-171. [10] Christensen U.R. and Aubert J. (2006) G. J. Int., 166, 97 - 114. [11] Garrick-Bethell I. et al. (2009) Science, 323, 356-359.