AN IMPACT DRIVEN DYNAMO FOR THE EARLY MOON.

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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 (Serenitatis, Crisium, Humboldtianum, Mendel-Rydberg, Moscoviense, and Nectaris) 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. In this scenario, large impact events unlock the Moon from synchronization, giving rise to energy dissipation at the core-mantle boundary and large-scale fluid motion in the core. Such a dynamo is capable of generating surface field strengths of several μT for several 10s of thousands of years, and can account for the presence of magnetic anomalies in some lunar impact basins.

Tidal instability. A huge amount of energy is stored in the spin and orbital motions of any planet, and the question is to know whether or not it can be efficiently transmitted to drive dynamo-capable core flows. A debate has persisted since the 60's concerning this issue [e.g., 6], and Malkus [7,8] proposed that inertial instabilities could be this efficient conveyer. Although this proposal was first rejected [9,10], it has since been proven that inertial instabilities are indeed highly energetic [11,12,13] and dynamo capable [14,15,16]. Inertial instabilities come from a parametric resonance between two inertial waves of the rotating flow and a large scale natural forcing (such as precession or tides).

We have performed a systematic study of the tide driven instability in a deformable rotating fluid sphere, where tidal deformations are mimicked by slight symmetric compressions of the outer core-mantle boundary [12]. A fully three-dimensional turbulent flow is excited as soon as the ratio between the ellipticity of the core-mantle 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, we are fully confident in considering this tidal instability as dynamo capable using a similar threshold [14,15,16]. 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 [17,18] 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.

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 $\sim2.0\times10^{-3}$, depending on the distance between the Earth and Moon. The difference in equatorial moments of inertia of the Moon (B-A) are not presently hydrostatic, and we use as a representative value a moment difference that is 10 times greater than the predicted hydrostatic value. The orbital period of the Moon is presently T_{orb}=27.32 days, but this could have been as low as 2.5 days shortly after the Moon formed.

Assuming synchronous rotation of the Moon, we find an Ekman number ranging between 3.0×10^{-12} today and $\geq3.0\times10^{-13}$ in the past. This implies that $\beta/\mathrm{E}^{1/2}>10$, and 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.

We considered two possible cases for dynamo generation: for the first, a large impact generates large-scale longitudinal librations [5], and in the second, the impact increases (or decreases) it rotation rate beyond synchronous rotation. We have evaluated these two scenarios for Earth-Moon separations ranging between 10 and 55 Earth radii. For the first case, libration angles up to ±90° were considered, and for the second, representative spin periods of the mantle after impact between 3 and 35 days were tested. By systematically varying these parameters, we have examined the possibility of generating a core dynamo using two conditions: (1) a sufficiently large growth rate of the excited parametric instability is required to establish a fully turbulent state before the Moon is resynchronized, and (2) a sufficiently vigorous core flow is necessary to reach magnetic Reynolds numbers larger than the threshold for dynamo action.

Our calculations show that the core flow could be unstable for the case of longitudinal librations, but that the typical growth times remain much longer than the typical resynchronization time. A dynamo driven by longitudinal librations is thus unlikely. On the other hand, if the Moon's rotation was desynchronized, a dynamo could be active over a wide range of Earth-Moon separations, as shown in Figure 1. This mechanism implies magnetic field strengths between 1-10 μT at the surface of the Moon that would be stable for durations between 10^3 to 10^5 years (Figure 2), These magnetic field strengths are consistent with the lunar sample based ~1μT paleofield determination of [19].

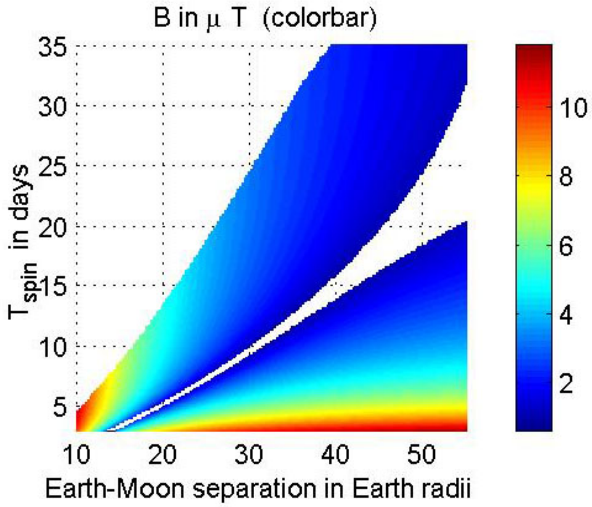

Figure 1. Estimated amplitude of the magnetic field strength at the surface of the Moon following a basin forming impact that desynchronizes the Moon's rotation.

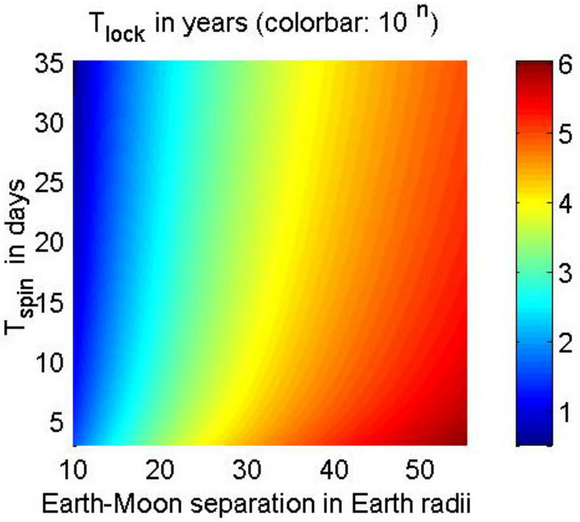

Figure 2. Estimated time of resynchronisation after an impact, during which a tidally driven dynamo could persist.

Conclusions. Large scale fluid flows in the lunar core set up following impact events are one possible manner of generating a lunar dynamo. A dynamo driven by longitudinal librations is unlikely, but if the Moon's rotation was desynchronized by a large impact, a dynamo could have been active for durations of 10^3 to 10^5 years with magnetic field strengths comparable to some paleomagnetic estimates. Transient tidally driven dynamos following large impacts thus constitute a plausible source for the fields that magnetized some portions of the lunar crust.

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