THE ANCIENT LUNAR DYNAMO: HOW TO RESOLVE THE INTENSITY AND DURATION CONUNDRUMS.

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Introduction: Modern paleomagnetic analyses of Apollo lunar samples indicate that the Moon possessed a strong surface magnetic field with intensities in the range 10-100 μT between at least 4.25 and 3.26 Ga [1-6]. The paleofield intensity subsequently decreased to below ~4 μT sometime between 3.56 and 3.19 Ga [7,8]. A core dynamo seems to be the only plausible explanation for this long-lived field, however, any model of the lunar dynamo should be able to explain both the early high-field epoch as well as the rapid decline to a lower field epoch.

The duration of the lunar dynamo will depend on the power source driving motions in the core to generate the magnetic field. Recent studies have demonstrated that driving the lunar dynamo through thermal convection [9,10] or thermo-chemical convection [11,12] may have the longevity necessary for the lunar dynamo, but cannot produce fields strong enough to explain the inferred intensities in the high-field epoch. Mechanical driving due to impacts [13] may explain some crustal fields associated with specific craters, but can't explain the majority of lunar magnetism.

Theoretical studies have demonstrated that mechanical driving due to mantle precession relative to the core may have enough power to drive the dynamo for a period of time after the Cassini transition [14]. In that study, scaling laws were used to determine that this mechanism could produce fields of enough strength to explain the high-field epoch, but numerical simulations of this process are challenging and have yet to demonstrate that dynamo action generated from precessional forcings will be capable of producing the field intensities necessary to explain the lunar crustal fields.

Here we propose a modification of this mechanical dynamo in which we consider the role of a solid inner core that is gravitationally locked to the precessing mantle. We use numerical dynamo simulations and scaling laws to demonstrate that this scenario results in novel magnetic instabilities that can explain the intensity and longevity of the lunar dynamo during the high-field epoch.

Method: We solve the full MHD equations in a spherical shell using the mMoSST core dynamics model [15] with modifications to include: (1) precession of the mantle relative to the fluid outer core and (2) an inner core that is forced to precess with the mantle. The parameters that we vary in our simulations are the angular rotation rate of the outer core (Ω_0) and the obliquity of the mantle (Ψ_M) which is directly related to the mantle precession angle. We use a precession rate consistent with each mantle obliquity angle in the simulations. For all our simulations we fix the inner core radius to be 0.5 of the total core radius and we use a magnetic Prandtl number of 1.

Results: For our simulations, we determined the threshold for dynamo action as a function of outer core rotation rate and mantle obliquity (Fig. 1). Since we are numerically constrained to use core rotation rates slower than lunar values, we extrapolated our results to lunar parameter values and found that the lunar dynamo would have been active with this mechanism from the time of the Cassini transition until the Moon reached a semi-major axis of ~42.5 $R_\oplus$.

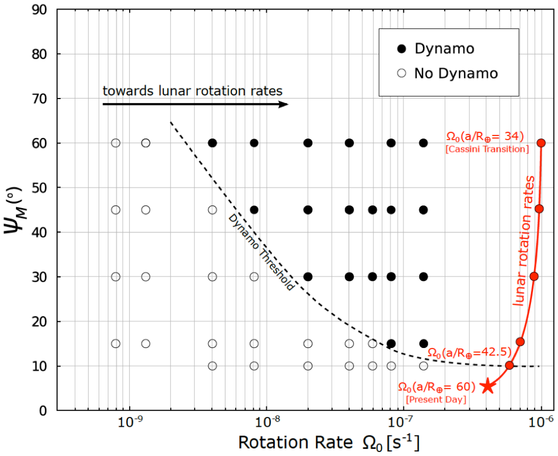

Figure 1. Summary of the parameter space explored. Filled black dots indicate models in which the dynamo did not decay. A dashed curve is drawn separating the two regions of the parameter space. Filled red dots mark the rotation rates of the Moon at various points in lunar history.

We also determined the surface field intensity in our simulations and extrapolated our results to lunar rotation rates (Fig. 2). We find that field intensity increases with mantle obliquity and that we can produce fields in the 10-100 μT range for obliquity angles greater than 30°.

Conclusions: By incorporating a solid inner core that is co-precessing with the mantle, we find numerical dynamo solutions that can explain the high-field magnetic epoch for the Moon, as well as the decline to lower field values when the mantle obliquity has decreased below ~30°. Below ~10°, we find the dynamo is no longer active with this mechanism. After this time, other driving mechanisms (e.g. thermo-chemical convection) would be required to explain younger crustal magnetic fields.

In the parameter regime we studied, precessional motions alone (i.e. without a co-precessing inner core) could not generate a dynamo. However, precessional instabilities may generate dynamo action at faster rotation rates than we have considered in our models or if core ellipticity and topography is incorporated. This may expand the region of parameter space where a mechanical dynamo can be active and will be the subject of future studies.

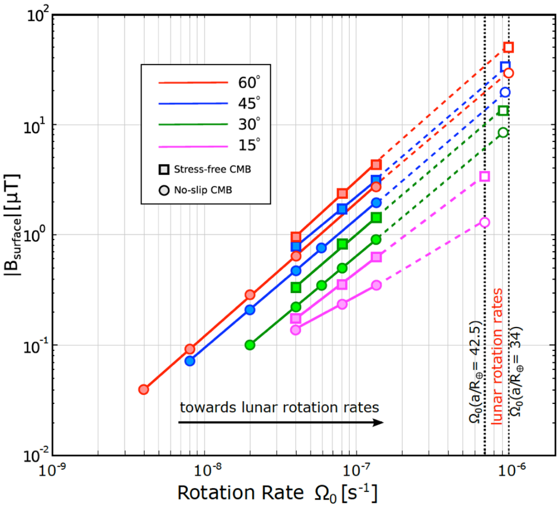

Figure 2: Surface magnetic field intensity as a function of rotation rate for various mantle obliquities. Dashed lines are drawn to extrapolate surface field intensities from simulations towards lunar values of rotation rate. The filled shapes are data points taken from simulation results, while empty shapes mark the predicted surface field intensity from the extrapolations.

References:

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