DRIVING AN EARLY LUNAR DYNAMO VIA MECHANICAL STIRRING. C. A. Dwyer, F. Nimmo, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz, CA 95064 (cadwyer@ucsc.edu)*, D. J. Stevenson, *Div. Geological & Planetary Sciences, Calif. Inst. Tech., Pasadena, CA 91125.*

Introduction A recent paleomagnetic study (1) has strengthened earlier suggestions (2) that lunar magnetic anomalies are due to an ancient dynamo, rather than an external source such as impacts (3). While the lunar paleomagnetic data are not conclusive (4), they do raise the question of how a lunar dynamo could be maintained, especially in light of work which suggests that a convective lunar dynamo would be difficult to maintain (5; 6).

Here we suggest that mechanical stirring, rather than thermal convection, produces a dynamo. The 18.6 year forced nutation of the lunar mantle results in differential motion between the core and mantle (7), resulting in turbulent motion within the core which might be capable of driving a dynamo. (8) recently examined the circumstances under which such differential motion would initiate; our goal is to relate, at least crudely, the resulting motion to the magnetic field intensity.

Theory We focus on the energetics of the system, though in reality the geometry of the flow generated by differential motion may also have an important role (see below). The power dissipated at the core-mantle boundary (CMB) at the present day is $6.0 \pm 1.6 \times 10^7$ W (9). This quantity depends on the equatorial inclination I_e and the mean motion n of the lunar orbit according to $P \propto n^3 \sin^3 I_e$, (9), where the lunar equatorial inclination is the angle between the lunar mantle spin axis and the ecliptic normal (which is nearly the same as the lunar liquid core spin axis (10)). Thus, to understand how the magnetic field may have evolved with time, we need to know how both n (or, equivalently, the semi-major axis a) and I_e have varied over time. We have used Model II of (11) to relate semi-major axis to time since formation and the relation of (12) between semi-major axis and obliquity to relate I_e and a (via $I_e =$ obliquity $- 5.1°$).

Given the relationship between a and I_e, as well as a prescription for how a evolves as a function of time, the power dissipated at the lunar CMB as a function of time t can be written:

$$P_\Sigma(t) = \left[\frac{a(t_n)}{a(t)}\right]^{9/2} \left[\frac{\sin I(t)}{\sin I(t_n)}\right]^3 P_\Sigma(t_n) \qquad (1)$$

$$= \left(2.8 \times 10^{20}\ \mathrm{W}\right) \frac{\sin^3 I(t)}{\left[a(t)/R_e\right]^{9/2}} \qquad (2)$$

Here P_Σ denotes the total power dissipated at the CMB, R_e the radius of the Earth and t_n the time at the present day.

Not all the power generated at the CMB is available to drive a dynamo: some fraction of that power is required to stir the core fluid with sufficient vigor to maintain it in an adiabatic state. The power available to generate a dynamo is $P_B = P_\Sigma - P_{ad}$. The power necessary to sustain an adiabat at the lunar CMB is $P_{ad} \approx 4.7 \times 10^9$ W. Since at the present day $P_\Sigma < P_{ad}$, the absence of a current lunar dynamo is consistent with this model. This analysis ignores the consequences of a putative sold inner core (13) and its likely growth over geologic time.

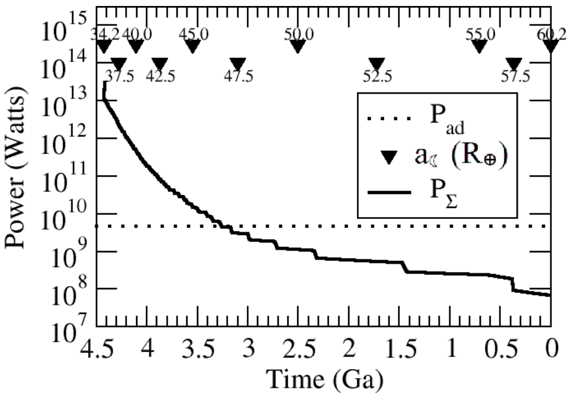

Figure 1: The total power deposited into the lunar core over time (P_Σ; eq 2). The power needed to sustain an adiabat is marked P_{ad} ($P_{ad} \approx 4.7 \times 10^9$ W). The lunar semi-major axis (in R_e) corresponding to various times is marked at the top of the plot in triangles. Discontinuities in line are an artifact of digitization of the a-I_e relationship.

Fig 1 shows the temporal evolution of the power dissipated at the CMB, P_Σ, compared with the adiabatic power, P_{ad}. The power dissipated rapidly decreases with time as the semi-major axis increases and drops below the adiabatic threshold at $a \approx 47\ R_e$. In our nominal evolution model this occurs at a time of 3.25 Ga, but other evolution models would result in other threshold times.

The power dissipated at early times (before 4 Ga) becomes very large, because of the large equatorial inclination. At these large equatorial inclinations, our parameterization for power dissipation is almost certainly inappropriate, so the large predicted powers prior to 4 Ga are very likely overestimates.

Below we present two separate models for generation of magnetic field based on the power deposited into the lunar core. The energetic approach adopted here is certainly extremely crude and in particular neglects the spatial pattern of the mechanically-driven flow, which may well be important. By adopting two different models with very different starting assumptions, we gain some insight into the likely robustness of our results.

Model 1. We assume that the magnetic field at the surface of the moon can be approximated by scaling the terrestrial field onto the Moon:

$$B_{1m}(P_{Bm}) = B_e(t_n) \frac{R_e^3}{R_m^3} \frac{R_{mc}^{5/2}}{R_{ec}^{5/2}} \frac{P_{Bm}^{1/2}(t)}{P_{Be}^{1/2}(t_n)} \qquad (3)$$

$$= 0.8\ \mu T \left(\frac{P_{Bm}}{10^{11}\ W}\right)^{1/2} \qquad (4)$$

where R_m is the lunar radius, R_{mc} and R_{ec} are the core radii for the Moon and Earth respectively, P_{Bm} and P_{Be} are the superadiabatic power for the Moon and Earth respectively, B_{1m} is the field strength predicted by model 1 at the surface of the Moon, and B_e is the Earth surface magnetic field strength. In this equation, the $5/2$ power is due to the geometry of scaling the cores, the ratio R_{mc}/R_{ec} accounts for the size difference of the cores, and the $(R_e/R_m)^3$ term is due to attenuation, assuming a predominantly dipolar field. The largest source of uncertainty in this approach is the uncertainty in the excess power for the Earth's core, P_{Be}. We have taken $P_{Be} = 10^{13}$ W, which will result in a conservatively small lunar field strength.

Model 2. For our second model, rather than scaling from the Earth, we will use a set of model results and direct scalings from (14). The largest single source of uncertainty in this model is in the calculation of the efficiency factor F. Although this factor does depend on the spatial distribution of the heating, it is the total power which really matters (14), and thus this uncertainty is unlikely to significantly affect our conclusions. The resulting field is given by:

$$B_{2,m}(R_m) = 4.4\ \mu T \left(\frac{P_{Bm}}{10^{11}\ W}\right)^{1/3} \qquad (5)$$

Here we have implicitly assumed that differential motion at the CMB results in turbulent motion extending over the bulk of the core. For this to occur, the flattening of the core ϵ has to exceed the dimensionless Ekman boundary layer thickness (e.g., 15; 16). Using the estimated present-day flattening of the lunar core (8), we find that the criterion for turbulent flow is met now and will be more strongly satisfied in the past. At very early times ($a \lesssim 26 - 29\ R_e$, (8)), the precession of the core will be locked to that of the mantle and no differential motion will result.

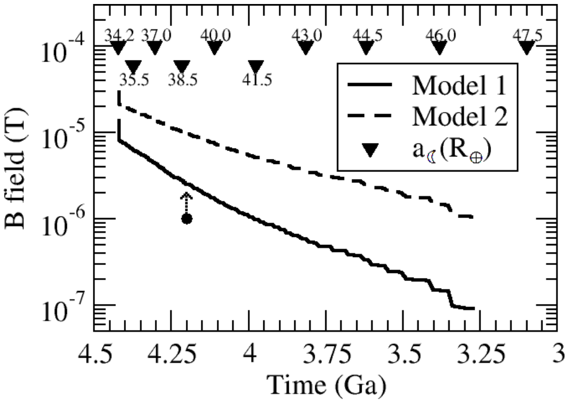

Figure 2: The lunar paleointensity predicted by our models (model 1: eq 3; model 2: eq 5). The constraint of (1) is plotted as a dot with an arrow. The lunar semi-major axis (in R_e) corresponding to various times is marked at the top of the plot. The conversion between semi-major axis and time was done using Model II of (11).

Results Fig 1 shows that the larger equatorial inclination and smaller semi-major axis at earlier times result in increased power available to drive the dynamo. Fig 2 shows how the surface field strength based on our two different scalings (equations 3 and 5) evolve with time. For both models, the predicted field strength drops to zero once the available power is less than the adiabatic value (3.25 Ga, $a \approx 47\ R_e$). The field strength increases at earlier times but at different rates; model 2 predicts systematically higher field strengths. Coincidentally, however, at the earliest times (before 4 Ga) the predicted field strengths are within a factor of 5 of each other. The predicted field strengths are in the range ~0.1-10 μT for model 1 and ~1-10 μT for model 2.

A recent minimum estimate of lunar paleointensity gives ~1 μT at 4.2 Ga (1) and is plotted on Fig 2 as a dot with an upwards arrow. The inferred minimum paleointensity is a factor of two smaller than that predicted by our model 1 and an order of magnitude smaller than that predicted by our model 2. This is an encouraging result. Furthermore, the specific orbital evolution model that we employed suggests that a dynamo could persist for more than 1 Gyr, significantly longer than any likely convection-driven dynamo and capable of explaining the billion-year record of lunar magnetization (2).

Discussion The results above suggest that sufficient energy was available to power a mechanically stirred dynamo for perhaps the first billion years of lunar history. However, before deriving any further conclusions, several caveats are in order.

First, and most fundamentally, by focusing on the energetics of the situation we have ignored the detailed flow patterns which arise from differential motion, which may be quite different from convectively-driven flows. Second, the fundamental relationship between dissipation and equatorial inclination (eq 2) is likely inappropriate at early times (before 4 Ga) when equatorial inclinations were large. Third, while the relationship between magnetic field intensity and lunar semi-major axis a is likely robust, the conversion of a to time is much more uncertain, as there are essentially no constraints between the time/location of the formation of the moon and 0.6 Ga when the geologic record begins (17). For instance, although in our nominal model, $a = 45\ R_e$ occurs at about 3.5 Ga, in other models this distance could occur sometime until ~2.5 Ga (18; 11; 19).

Despite these caveats, however, the results presented here are encouraging enough to warrant further investigation of a mechanically-driven lunar dynamo. The importance of this and future studies is that they provide a potential link between paleointensity measurements and orbital evolution. In particular, one could even envisage a situation in which the paleointensity record could be used to calibrate the rate of orbital evolution, and thus the dissipation within the Hadean Earth.

Summary We have examined the energetics of a lunar dynamo powered by differential motion across the CMB. Both models predict a lunar paleointensity somewhat in excess of the 1 μT minimum value deduced in (1) as well as a dynamo duration of ~ 1 Gyr, suggesting that differential rotation is a possible method of driving an ancient lunar paleodynamo.

References [1] Garrick-Bethell, I. et al., Sci 323, 356-359, 2009. [2] Cisowski, S.M. et al., JGR 88, A691-A704, 1983. [3] Hood, L.L. et al., JGR 96, 9837-9846, 1991. [4] Lawrence, K. et al., PEPI 168, 71-87, 2008. [5] Stegman, D.R. et al., Nat 421, 143-146, 2003. [6] Takahashi, F. & Tsunakawa, H., GRL 36, L24202-L24205, 2009. [7] Yoder, C.F., Ph Tr R So A 303, 327-338,1981. [8] Meyer, J. & Wisdom, J., Icarus in press (2010), DOI: 10.1016/j.icarus.2010.09.016. [9] Williams, J.G. et al., JGR-P 106, 27933-27968, 2001. [10] Goldreich, P., JGR 72, 3135-3137, 1967. [11] Walker, J.C.G. et al. in: *Earth's Earliest Biosphere: its Origin and Evolution*, Princeton Un Pr, 1983, pp 260-290. [12] Ward, W.R., Sci 189, 377-379, 1975. [13] Weber, R.C. et al., DI33B-03, AGU Fall 2010. [14] Christensen, U.R. et al., Nat 457, 167-169, 2009. [15] Kerswell, R.R., Geophys Astro Fluid Dyn 72, 107-144, 1993. [16] Aldridge, K. et al., PEPI 103, 365-374, 1997. [17] Williams, G.E., Rev Geoph 38, 37-59, 2000. [18] Ooe, M. et al., in: *Variations in Earth rotation*, IUGG:AGU, pp 51-57, 1990. [19] Webb, D., Geophys J R Astro S 70, 261-271, 1982.