TIDAL DISSIPATION IN THE EARLY LUNAR MAGMA OCEAN AND ITS ROLE IN THE EVOLUTION OF THE EARTH-MOON SYSTEM.
F. Nimmo[1] and E.M.A. Chen[1], [1]Dept. Earth and Planetary Sciences, University of California Santa Cruz, 1156 High St, Santa Cruz CA 95064 (fnimmo@es.ucsc.edu)

Summary: Dissipation in the Earth drove the Moon outwards over time. As it did so, the Moon's obliquity increased, reaching a maximum at the so-called Cassini state transition at a distance of ~30 Earth radii (R_E) [1]. High satellite obliquities can result in dissipation which will damp the inclination [2]. Thus, if the Moon were very dissipative early in its history, it could not have achieved its current inclination.

A lunar magma ocean is potentially very dissipative. Following [3], we have developed an analytical description for obliquity-driven tidal dissipation in shallow oceans [4]. We incorporate this mechanism into a coupled thermal-orbital evolution model [5]. We find that the lunar magma ocean must have solidified prior to encountering the Cassini state transition to avoid damping of the lunar inclination via obliquity tides.

Geochronology suggests that the lunar magma ocean solidified on a timescale ~100 My [6]. Thus, the Moon must have taken >100 My to reach ~30 R_E, which limits the amount of dissipation which could have happened within the early Earth. The early Earth was a factor ~10^3 less dissipative than it is today, and probably lacked global oceans.

Model: The model consists of three coupled components:

1) The orbital code, based on [5]
2) The calculation of dissipation in the magma ocean, based on [4]
3) The thermal evolution of the magma ocean.

Orbital Evolution. We adopt the same approach as [5], correcting several typographic errors. We incorporate dissipation in the magma ocean by writing the Mignard A parameter [7] (which compares dissipation in the Moon to that in the Earth) in a non-standard form:

$$A_i = -\frac{2}{3}\frac{M}{m}\left(\frac{a}{R_E}\right)^5 \frac{\dot{E}_M}{k_{2E} m \Delta t\, n^4 a^2}\frac{\cos i}{\sin^2 i}$$

Here M and m are the mass of the Earth and Moon, a is the semi-major axis, R_E is the radius of the Earth, k_{2E} and Δt are the Love number and tidal time lag of the Earth, i is the inclination and $\dot{E}_M$ is the obliquity-driven dissipation in the ocean.

Tidal dissipation in a magma ocean. A synchronous satellite with a finite obliquity can experience strong tidal dissipation in a liquid layer [3,4]. Below we adopt an approach [4] in which the dissipation is assumed to arise through bottom friction as parameterized by a drag coefficient C_D. This description is often adopted in models of terrestrial ocean dissipation [8]. The resulting obliquity-driven dissipation rate is given by:

$$\dot{E}_M = \frac{108\pi}{25}\frac{\rho h \nu \Omega^8 R_M^{10}}{\left(\frac{9}{25}\Omega^6 R_M^8 + 144\nu^2 g^2 h^2\right)}\theta_0^2$$

Here ρ is the magma ocean density, Ω is the rotation angular frequency, R_M is the radius of the Moon, g is the surface gravity, h is the thickness of the magma ocean and θ_0 is the obliquity. Note that dissipation rate goes as obliquity squared, just as it does for solid body dissipation [9]. The quantity ν is the turbulent diffusivity, which depends on C_D according to a scaling relationship derived from numerical experiments described in [4], and is typically 10^3-10^4 m^2s^{-1}.

To calculate the obliquity θ_0 , we adopt the approach used in previous studies [10,11] and assume that the Moon is in a damped Cassini state. The obliquity then depends on the orbital parameters and the degree-2 gravity coefficients of the Moon and the Earth. Since both bodies are expected to be hot early in their histories, we assume that they are both hydrostatic, so that the Darwin-Radau relationship can be used to calculate their gravity coefficients based on their moments of inertia and spin rate.

Magma ocean solidification. We model magma ocean solidification as a Stefan problem [12] except that the heat flux into the base of the solidifying crust is given by $\dot{E}_M / 4\pi R_M^2$ so that the cooling rate depends on the tidal heat production as well as the current lid thickness.

Results: Figure 1 shows how different parameters evolve with semi-major axis when magma ocean dissipation is *not* included. Different curves represent different degrees of dissipation within the Earth, which controls how rapidly the semi-major axis evolves (**e**). Without dissipation, the magma ocean takes ~30 Myr to solidify completely (**c**). The obliquity undergoes a large excursion at ~30 R_E when the Cassini state transition occurs (**b**). This would cause high dissipation if a magma ocean were present, and significant damping of the inclination (**a**).

To avoid inclination damping, the magma ocean must have solidified *before* the Cassini state transition occurs. Thus, the outwards evolution of the Moon must have been slow, so the Earth was not very dissipative. Figure 2 shows the outwards motion of the

Moon for different Earth tidal time lags Δt. A Δt of < 1s is required, compared with the present-day value of 600 s. A low-dissipation Earth and slow outwards motion of the Moon are consistent with a molten Earth possessing a thick, blanketing atmosphere [13].

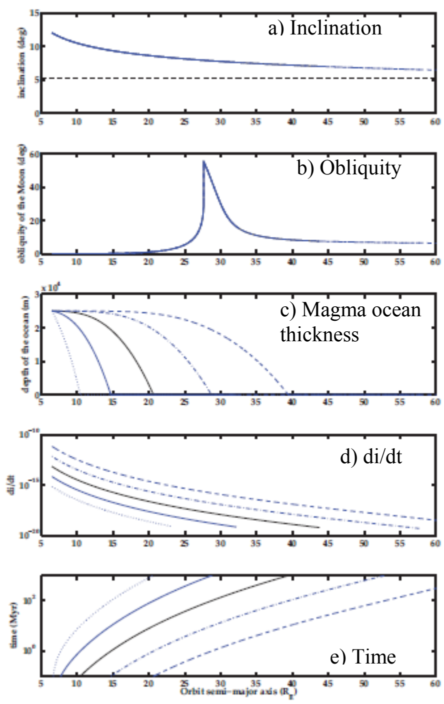

Figure 1. Evolution of lunar parameters as a function of semi-major axis for the case with *no dissipation* in the magma ocean. Different lines correspond to different degrees of dissipation within the Earth. Solid black line represents Δt=10s; other lines differ by factors of 10.

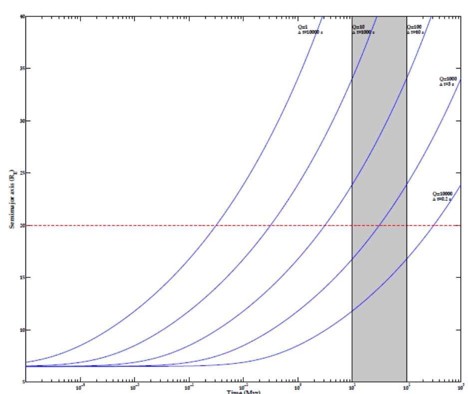

Figure 2. Outwards motion of the Moon for different time lags Δt in the Earth. The shaded region marks the lifetime of the magma ocean and the red line the onset of the Cassini state transition.

Figure 3 shows the evolution of the orbit and magma ocean when dissipation is included. As expected, inclination damps rapidly (**a**), while the lifetime of the magma ocean is prolonged due to internal heating (**c**). A dissipative magma ocean is inconsistent with the present-day orbital configuration of the Moon, and suggests that the magma ocean solidified before the Cassini state transition was reached.

Discussion: The slow outwards evolution required to permit the magma ocean to solidify before reaching the Cassini state transition implies an Earth ~10^3 times less dissipative than at present, consistent with the effects of a thick atmosphere blanketing a molten Earth [13]. Since the bulk of the dissipation occurs in the oceans today, this result also implies that the Hadean Earth lacked global oceans of the kind present now.

References: [1] Ward WR, Science 189, 1975. [2] Chyba CF et al., Astron. Astrophys. 219, 1989. [3] Tyler RH, Icarus 211, 2011. [4] Chen EMA et al., Icarus 229, 2014. [5] Meyer J et al., Icarus 208, 2010. [6] Elkins-Tanton LT et al., EPSL 304, 2011. [7] Mignard F, Moon Planets 20, 1979. [8] Jayne SR, St Laurent LC, GRL 28, 2001. [9] Wisdom J, Icarus 193, 2008 [10] Chen EMA, Nimmo F, Icarus 214, 2011. [11] Siegler MA et al. JGR 116, 2011. [12] Turcotte and Schubert, Geodynamics, 2002 [13] Zahnle K et al., Space Sci. Rev. 129, 2007.

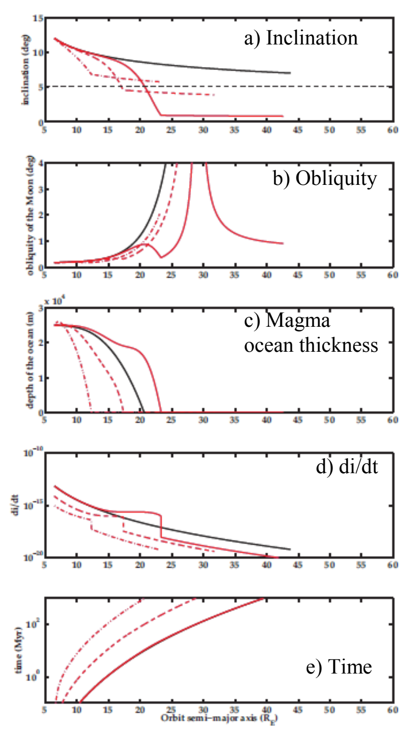

Figure 3. Evolution of lunar parameters when dissipation in the magma ocean is included (cf. Fig 3). Note the rapid damping of inclination. Black line is when dissipation does not occur, red lines are for different values of Δt.