LUNAR BASAL MAGMA OCEAN MAINTAINED BY PRECESSION-DRIVEN VISCOUS FRICTION

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Introduction: Lunar paleomagnetism suggests a long-lived dynamo and a magnetic field intensity of tens to $\sim 100 \mu$T on the lunar surface between 4.25 and 3.56 Ga [1, 2, 3] that are hard to be explained by the core-cooling driven by lunar mantle convection [4]. Precession-driven viscous friction at the core-mantle boundary (CMB) was suggested to be a possible reason for the strong early magnetic field [5]. Nevertheless, this hypothesis was never examined in the context of thermal evolution modelling. Viscous friction at the CMB elevates the local temperature and tends to suppress the core convection. It also remains unclear whether the heated lunar core could remelt the overlying solid mantle, forming a basal magma ocean (BMO), i.e. a totally molten layer at the base of the mantle, that complicates the operation of lunar core dynamo [6, 7]. Using 1-D thermal evolution modelling, we examine here the influence of precession-driven viscous friction on the thermal evolution of deep lunar mantle and the evolution of lunar magnetism.

Methods: We initiate the thermal evolution modelling from $\sim 4.4$ Ga that characterizes the solidification of lunar magma ocean [8]. Thermal evolution of deep lunar mantle is divided into two phases, core-cooling phase and BMO phase. When the CMB temperature is lower than the liquidus at the base of the mantle, the thermal evolution of deep lunar mantle is dominated by core-cooling, heat loss via solid-mantle convection, viscous friction at CMB and the radiogenic heat from a dense ilmenite-rich layer over the CMB relating to an overturn of the molten ilmenite-rich material is the principal contributor of radiogenic heat in the BMO. Accompanying with the growth and decay of the BMO, latent heat is absorbed or is released at the BMO’s outer boundary, balancing the heat loss via solid mantle convection, radiogenic heat and viscous friction heat. For the typical temperature (2000–2500 K) and pressure ($\sim 4.5$ GPa) at the base of lunar mantle, the density of the molten IBC is estimated to be $\sim 3700$ kg/m$^3$, higher than the density of solid lunar mantle $\sim 3204$ kg/m$^3$. Thus, we assume the BMO to be stable over the CMB.

Assuming the solid mantle to be weakly coupled with the liquid portion, i.e. the molten core for the core-cooling phase and BMO for the BMO phase, the power of precession-driven viscous friction is determined by a scaling relationship [13]

$$P_f(t) \approx P_{f,0} \frac{k'}{\kappa_c} \frac{\rho'(t)}{\rho_c} \left[ \frac{r'(t)}{r_c} \right]^6 \left[ \frac{a(t)}{a_0} \right]^{-9/2} \left[ \frac{\sin I_e(t)}{\sin I_{e,0}} \right]^3$$

(2)

where $k'$ the drag coefficient, $\kappa_c$ the drag coefficient of the present lunar core, $\rho'$ the density of the liquid portion, $\rho_c$ the core density, $r'$ the radius of the liquid portion, $r_c$ the core radius, $a$ the semi-major axis of lunar orbit, $I_e$ the tilt angle from lunar equator to the ecliptic plane, $a_0$ and $I_{e,0}$ the present values of $a$ and $I_e$ respectively. As an example, we use here the nominal orbit model in ref. [5] to constrain the time evolution of the semi-major axis. The tilt angle is determined from the obliquity-orbit relation in ref. [14] and the tile angle = obliquity - 5.76° [5]. Core-mantle decoupling occurs for $a \approx 26$–29$R_e$ ($R_e$ is the Earth’s radius) [15]. We choose $a = 29R_e$ as the point for the initiation of core-mantle friction.

Results and Conclusions: Figure 1 shows the time evolution of BMO thickness for several reference viscosities. In all cases, BMO is generated around $\sim 4.2$ Ga. The longevity and maximum thickness of the BMO depend strongly on the reference viscosity. For a reference viscosity of $5 \times 10^{19}$–$1 \times 10^{21}$ Pa s, the lifetime of the BMO varies from $\sim 200$ to $\sim 500$ Myr and maximum BMO thickness from $\sim 7$ to $\sim 37$ km.

The presence of Fe-Ti oxides in the deep lunar man-
tle can elevate the electrical conductivity of basal melt to \( \sim 10^3 \) S/m [16] and a BMO dynamo is thus plausible. The thermal convection in BMO maintains a dynamo if the electrical conductivity of basal melt is higher than the critical value, i.e. \( \sigma_{cr} = Rm_{cr}/UL\mu_0 \) where \( Rm_{cr} \) is the critical Reynolds number (\( \sim 50 \)), \( U \) the characteristic velocity, \( L \) the characteristic length, \( \mu_0 \) the magnetic permeability in vacuum [17]. Here we take BMO thickness as the characteristic length and estimate the characteristic velocity of BMO convection by mixing length theory (MLT). As shown in Figure 2a, the BMO dynamo requires a critical electrical conductivity of \( \sim 10^9 \) S/m. Hence, the thermal convection in the BMO cannot maintain a dynamo.

Nevertheless, BMO complicates the operation of lunar core dynamo. We firstly estimate the velocity of core convection from the convection-driven heat flux by the MLT velocity law and then give the magnetic field intensity on the lunar surface by the power-based scaling law (MLT). From \( \sim 4.2 \) Ga, we observe a growing BMO shuts off the core dynamo. When BMO decays, the core dynamo is activated again and triggers a magnetic field between 1 and 10 \( \mu \)T. From \( \sim 4.2 \) Ga, the growing BMO shuts off the core dynamo. When BMO decays, the core dynamo is activated again and triggers a magnetic field between 1 and 10 \( \mu \)T on the lunar surface.

Early activation of core dynamo is favoured by the remnant magnetism of troctolite sample 76535 acquired at \( \sim 4.25 \) Ga [18]. Although the age ordering of the Nectarian basins is still poorly constrained, the shut-off of core dynamo accompanying BMO may provide a potential explanation for why half of the Nectarian impact basins were not magnetized [19]. The magnitude of lunar paleomagnetic field is hard to be explained by our model. In fact, we just considered a core dynamo driven by the thermal convection. Precession may induce other fluid instabilities in the lunar core that may affect the intensity of surficial magnetic field at global or regional scale [20]. In future investigations, the influence of precession on the pattern of core convection must be examined.

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