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Thermal evolution of early solar system planetesimals and the possibility of sustained dynamos

M. Glenn Sterenborg[a,*], John W. Crowley[b]

[a] Department of Geosciences, Princeton University, Princeton, NJ 08544, USA
[b] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA

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ABSTRACT

We present a study investigating the possible presence and longevity of a stable dynamo powered by thermal convection in early solar system planetesimals. We model the thermal evolution of planetesimals that start from an initially cool state. After melting, core formation, and onset of mantle convection have occurred, we use a numerical model that relies on thermal boundary layer theory for stagnant lid convection to determine a cooling rate and thermal boundary layer thickness that are dynamically self consistent. We assess the presence, strength and duration of a dynamo for a range of planetesimal sizes and other parameters. The duration of a dynamo depends foremost on the planetesimal's radius. Given a particular magnetic field strength and dynamo duration we are able to place a constraint on the minimum radius of planetesimals, for example: bodies smaller than ~ 500 km will be unable to generate a dynamo with magnetic field strength of the order of 20 μT for a duration of 10 Myr or longer. We find that dynamo duration also depends, to a lesser extent, on the effective temperature dependence of the mantle viscosity and on the rotation rate of the body. These dependencies are made explicit by our derivation of an analytical approximation for the cooling rate of a planetesimal and its dynamo duration.

1. Introduction

Our solar system began when the first solids condensed in the Sun's protoplanetary disk and the subsequent dust grains collected to form the first small bodies orbiting the Sun. Either by means of gravitational instability (Cuzzi et al., 1993; Youdin and Shu, 2002) or through gradual aggregation (Weidenschilling and Cuzzi, 1993) solid bodies several kilometers in size, planetesimals, were generated (Chambers, 2004; Weidenschilling and Cuzzi, 2006). In a process called runaway growth, gravitational focusing and dynamic friction then served to accrete these planetesimals together, dwindling their numbers to a handful of oligarchic planetary embryos with masses between 0.01 and 0.1 Earth masses (Thommes et al., 2003; Chambers, 2004). Gravitational interactions between the oligarchs led to massive collisions, ultimately forming the final terrestrial planets.

Of the eight planets, five dwarf planets, hundreds of moons and countless small solar system bodies, thus far only a handful have been observed to possess a dynamo generated magnetic field at one time (Stevenson, 2003). The understanding of the timing, origin, as well as the processes governing these dynamos, remains incomplete. However, in recent literature an avenue of research has emerged which may yield new insights as paleomagnetic arguments have been presented in support of early dynamos in meteorite parent bodies (Weiss et al., 2008, 2010). Uniformly magnetized angrites, i.e., achondritic meteorites, revealed the potential for an angrite parent body that had an internally generated magnetic field present during their formation with an intensity up to a few tens of microtesla (Weiss et al., 2008, 2010). Building on this work, and relying on continuous accretion of new chondritic material, a further argument was made in favor of a differentiated planetesimal sustaining a dynamo whilst maintaining an undifferentiated outer crust in accordance with observations of magnetized CV chondrites (Elkins-Tanton et al., 2011). Such early solar system planetesimals may thus represent novel realizations of planetary dynamos which may add to our understanding of them.

Several conditions must be met for a planet(esimal) to have a dynamo. The body must contain a sufficiently electrically conducting fluid layer. This fluid must experience convective motions with enough vigour to render the magnetic Reynolds number, a measure of flow complexity, $Re_m = u_c l/\lambda > O(10 - 10^2)$. Here u_c and l are the characteristic fluid speed and length scale, respectively. l is typically chosen as the depth of the fluid layer, however, an appropriate choice of u_c depends on the dominant force balance in the fluid layer (Christensen, 2010). $\lambda = 1/\mu_0\sigma$ is the magnetic diffusivity, μ_0 is the vacuum magnetic permeability and σ is the

* Corresponding author.
E-mail address: msterenb@princeton.edu (M. Glenn Sterenborg).

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electrical conductivity. A source of energy must be present to maintain these convective motions against ohmic dissipation in the fluid (Buffett, 2002; Gaidos et al., 2010; Monteux et al., 2011). This can take the form of a heat flow out of the layer that exceeds the amount of heat that can be transported conductively (for a thermally driven dynamo), or a release of latent heat and the expulsion of light, buoyant elements during iron solidification (for a compositionally driven dynamo).

It is thus clear that any investigation into the presence and duration of a planetary dynamo ultimately reduces to several key questions. Did the body experience enough heating to segregate the metal and silicate and form a liquid core? Is the body cooling sufficiently fast to provide a source of energy for convective motions in the core? An understanding of a body's thermal history is therefore paramount to any dynamo investigation.

The thermal evolution of an early solar system planetesimal is governed by several factors. The start time (relative to the formation time of CAIs) and rate of accretion of a planetesimal determines the amount of short-lived radionuclides, ^{26}Al and ^{60}Fe (Urey, 1955), that are present and contribute to internal heating, possible melting and differentiation of the body. Furthermore, the accretion rate, and how it is treated in models, impacts the peak central temperatures in the body, i.e., the maximum temperature the planetesimal cools down from (Merk et al., 2002; Šrámek et al., 2012). To what extent, and how fast the planetesimal experiences melting (Ghosh and McSween, 1998; Hevey and Sanders, 2006; Sahijpal et al., 2007) sets the stage for planetesimal differentiation and core formation (Ghosh and McSween, 1998; Senshu et al., 2002; Sahijpal et al., 2007; Gupta and Sahijpal, 2010). In practice, this sequence of events may have occurred, to some degree, simultaneously (Merk et al., 2002). The dynamics and time scales of metal–silicate separation and core formation has been the subject of much debate (Stevenson, 1990; Golabek et al., 2008; Ricard et al., 2009; Monteux et al., 2009; Samuel et al., 2010) and will not be treated here. Models of planetesimal thermal evolution tend to solve the 1D heat transport equation in some form (Ghosh and McSween, 1998; Merk et al., 2002; Hevey and Sanders, 2006; Sahijpal et al., 2007; Weiss et al., 2008, 2010; Elkins-Tanton et al., 2011), and convection in the post-differentiated mantle, if treated at all, is approximated by increasing the thermal diffusivity in the mantle by several orders of magnitude at a certain melt or temperature threshold (Hevey and Sanders, 2006; Gupta and Sahijpal, 2010). Furthermore, these models either fix the thickness of the outer conducting thermal boundary layer (often referred to as the 'lid') or assume a steady state process in order to determine its thickness. Neither of these approaches is appropriate when addressing the transient (warming/cooling) state of the planetesimal.

The present work has several objectives. By explicitly accounting for mantle convection we determine the thickness of the outer thermally conducting boundary layer that is dynamically self-consistent with the convective heat flow from the interior of the planet(esimal). We construct a thermal evolution model and address the requirements for the presence of a thermally driven dynamo and the key model parameters involved in determining its longevity for a range of planetesimal sizes. We also assess the notion that carbonaceous chondrites are the remains of the crust of a partially differentiated magnetized body (Elkins-Tanton et al., 2011; Sahijpal and Gupta, 2011).

1.1. A simple energy envelope

Before discussing our model we present a simple energy balance calculation that places lower bounds on the size of a planetesimal that is able to support a dynamo of a specified minimum magnetic field strength and duration. Given a specified accretion age for a planetesimal we can *a priori* calculate the maximum core temperature change $\Delta T_{max} = T_c - T_i$, above the initial temperature of the core T_i. Here we assume that all available heating goes into warming the core and neglect any latent heat effects. T_c is the core temperature. Clearly this is an upper bound for ΔT_{max} as some heat would have been lost due to cooling and heat would be also be required to warm the mantle and overcome any latent heat requirements. A simplified energy balance then yields

$$\rho_c V_c c_{p_c} \Delta T_{max} = M_p \frac{H_0 C_0}{\lambda_{Al}} e^{-\lambda_{Al} t_a} \tag{1}$$

where ρ_c, V_c, and c_{p_c} are the core density, volume and specific heat, respectively, M_p is the mass of the planetesimal, H_0 is the internal heating rate of ^{26}Al, and C_0 is the concentration of ^{26}Al in units of kg per unit kg of planetesimal. t_a is the time after CAI at which accretion occurs (assumed instantaneously) and λ_{Al} is the decay constant of ^{26}Al. The right hand side represents the energy provided by radiogenic heating. This can be re-arranged to give

$$\Delta T_{max} = \left[1 + \frac{\rho_m V_m}{\rho_c V_c}\right] \frac{H_0 C_0 e^{-\lambda_{Al} t_a}}{c_{p_c} \lambda_{Al}} \tag{2}$$

where we have used $M_p = \rho_m V_m + \rho_c V_c$ for the mass of the planetesimal. Eq. (2) gives an upper bound on the temperature that the core could reach with the available energy from internal heating. Fig. 1 plots ΔT_{max} (black lines) for accretion times of $t_a = 0$ Myr, $t_a = 1$ Myr, and $t_a = 2$ Myr.

We now consider the minimum core temperature change ΔT_{min} required to maintain a minimum heat flux of $F_{c_{min}}$ from the core for a duration of time Δt. This is simply

$$\Delta T_{min} = \frac{A_c F_{c_{min}}}{\rho_c V_c c_{p_c}} \Delta t \tag{3}$$

where A_c is the core surface area.

Different scaling laws may be deemed appropriate to estimate the core convective speed u_c depending on the leading order force

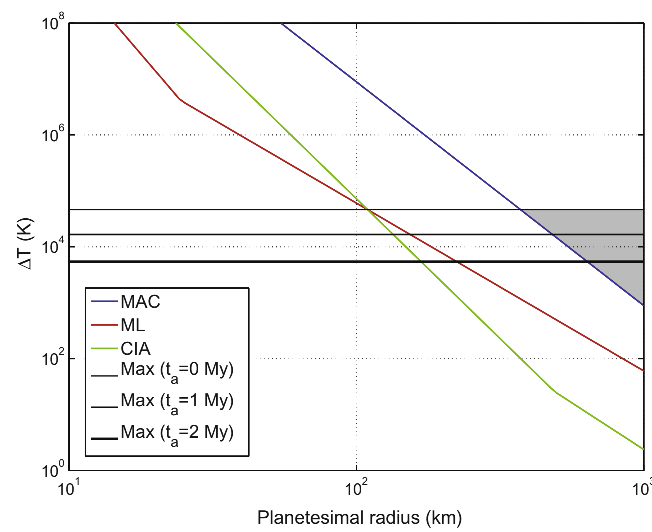

Fig. 1. The horizontal black lines represent the maximum achievable temperature in the core above its melting temperature for different accretion times. The minimum required core temperature for a dynamo of approximately 20 μ*T* which persist for 10 Myr is indicated by the colored lines. The blue line is based on a scaling law which derives from a balance between magnetic, buoyancy and Coriolis (*MAC*) forces in the core where we have used a rotation period of 10 h. Similarly, the red and green lines are based on mixing length theory (*ML*) and a force balance between Coriolis, inertial and buoyancy forces (*CIA*). The grey triangle indicates an example of allowable radii for planetesimals accreted at 0 Ma and using the *MAC* scaling law. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)