Why might Planets and Moons have Early Dynamos?

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Among the terrestrial planets and moons of the inner Solar System, Mars and the Moon record evidence for early and short-lived, (few hundred Myr) internally generated magnetic fields [1]. Despite its small size, Ganymede has currently an intrinsic dipolar magnetic field plausibly related to a dynamo [2]. Large meteoritical impacts play a major role during the early stages of planetary formation. Collision between an impactor and a protoplanet leads to a local temperature increase ΔT_0 above the impact site. For impactors falling at escape velocity, the temperature increase is mainly a function of the planetary radius R ($\Delta T_0 \sim R^2$) and its rheological properties [3]. For sufficiently large impacted planets, the temperature increase can eventually overcome the melting temperature of the metallic phase and metal-silicate separation can occur [4]. As the metallic phase, mainly composed of iron, is denser than the surrounding silicate material, it will sink towards the center of the impacted body as a diapir. The radius of this metallic diapir R_{Fe} is a function of the impactor radius and $R_{Fe}^3 = 3 f_0 R_{imp}^3$ with f_0 the volumetric fraction of metal.

Here we address whether processes governing core formation through Fe-segregation from large impacts might lead to dynamo action. We use the numerical model of [4] to identify R_{Fe}, R and the viscosity $\eta(T)$ required for dynamo action. In particular, we show that the accretion conditions determine whether or not a planet or a moon can have an early magnetic field.

Conditions for an early magnetic field

Two conditions are required to drive a dynamo on a growing planet. The heat flow out of the core Q must exceed the adiabatic value Q_A such that convection can occur [5, 6] and the ratio of the rate at which gravitational potential energy is released by convection Q to the rate of ohmic dissipation Φ must exceed a critical value [7, 8]:

$$\frac{Q}{\Phi} > \frac{1}{\epsilon_T}. \qquad (1)$$

Here, ϵ_T is the Carnot-style efficiency for the thermal convection (we do not consider here the effect of chemical convection or the presence of an inner core). ϵ_T is given by [7], and is

$$\epsilon_T = \frac{0.8\pi}{3}\frac{\alpha_{Fe} G \rho_{Fe} R_{Fe}^2}{C_{p,Fe}}\left(1 - \frac{Q_A}{Q}\right), \qquad (2)$$

where ρ_{Fe}, α_{Fe} and $C_{p,Fe}$ are the density, the thermal expansion coefficient and the specific heat capacity of iron and G is the gravitational constant.

Models

During the sinking of the metallic diapir towards the centre of the planet, a fraction of potential energy is converted into heat in the metallic diapir via viscous dissipation. To characterize the dynamics of the metallic diapir, we adapt numerical models developed by [4] in spherical axisymmetric geometry. The dimensionless governing equations solved in our numerical models are continuity, momentum conservation and conservation of energy.

We use a temperature dependent viscosity and a gravity that depends on radius. As this study focuses on the thermal state of the metallic phase once at the centre of the planet, we do not consider dynamical effects of the purely silicate phase. The thermo-chemical state just after the impact is simplified to that of a spherical drop of metallic phase with radius R_{Fe} and temperature $T = T_0 + \Delta T_0$ surrounded by undifferentiated cold material. Once at the center of the undifferentiated planet, the metallic diapir will be referred to as the protocore.

Results

To determine whether or not a dynamo is initiated after an impact, we monitor the heat flow Q across the protocore-mantle boundary as a function of time for a range of $R - R_{Fe}$ conditions (see Fig. 1 and 2). We stop calculations at 300 Myr because of the potential subsequent onset of mantle convection which is beyond the scope of this study. In all sets of planetary and metallic diapir radii studied here $Q >> Q_A$. Consequently, the condition for the presence of a dynamo from the combination of Eq.1 and Eq.2 simplifies to:

$$\frac{Q}{\Phi} > \frac{3}{0.8\pi}\frac{C_{p,Fe}}{G\alpha_{Fe}\rho_{Fe}R_{Fe}^2}, \qquad (3)$$

Figure 1 shows Q/Φ as a function of the impacted planet radius for different iron diapir sizes and times and analytical models for different rheologies. Figure 2 shows Q/Φ as a function of the size of the metallic diapir for different planet sizes in uniform viscosity cases. The black dashed line represents the condition required to get a dynamo from Eq.3. Results show that a dynamo is difficult to initiate with a small volume of metallic phase

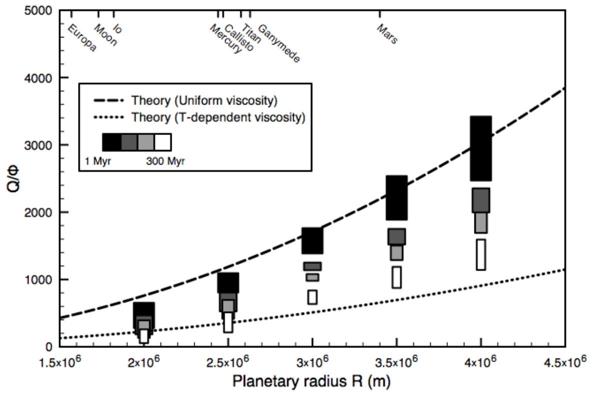

Figure 1: *Temporal evolution (from black to white) of the ratio Q/Φ as a function of the planetary radius. For each planetary radius, we used different diapir sizes. The length of the rectangles represents the variation of Q/Φ for the different diapir sizes used. The width of each rectangle is arbitrary. Theoretical evolution of Q/Φ for uniform viscosity or $a = 0.2$ is shown in black dashed line. For temperature dependent viscosity, $a = 0$ (black dotted line) represents the case of high viscosity contrast between hot and cold material. Planetary and moon radii of small solar system objects are indicated on the top x-axis (From [9]).*

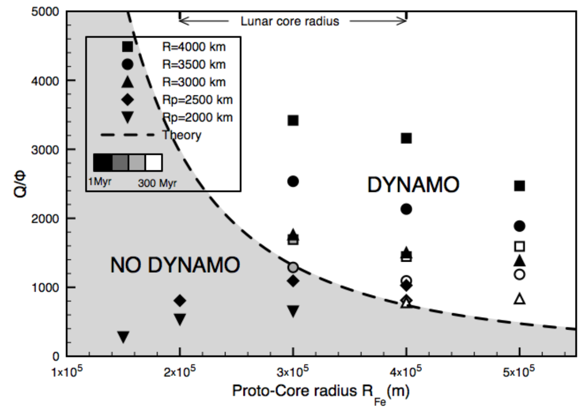

Figure 2: *Q/Φ 1 Myr after the diapir reaches the center of the impacted planet as a function of the metallic diapir radius (black symbols). The symbol shape is related to the radius of the impacted planet. The black dashed line represents the threshold expression from Eq.3. Above this dashed line (white domain) a dynamo is plausible, while below it no dynamo is generated. The ranged estimates of the lunar core radius is indicated on the top x-axis. If Q/Φ after 1 Myr is within the dynamo domain, a second symbol represents Q/Φ for the last time t (50 Myr, 100 Myr or 300 Myr) at which a dynamo is still observed. The fill color of the second symbol is a function of time (from dark grey to white) (From [9]).*

(i.e. small impactors). However, once the protocore radius is larger than 300 km (i.e. $R_{imp} > 375$ km), an early dynamo can occur during 100 Myr on a 3500 km radius planet. As the planet size and the protocore size increase, the duration of the early dynamo is longer (more than 300 Myr). Consideration of a large viscosity contrast between hot iron and cold undifferentiated material only reduces the duration of the early dynamo by a factor 4.

Discussion and conclusions

These results provide an important link between the accretion and differentiation histories of the terrestrial planets and moons and their potential early magnetic fields. They underline that the presence or absence of an early magnetic field on a planet could be related to its accretionary history. Hence, a 375 km radius impact (i.e. $R_{Fe} = 300$ km) on a Mars-size ($R = 3400$ km) or larger undifferentiated planet can initiate a dynamo that would persist for ~ 100 Myr (Fig. 2).

Such a scenario is difficult to envision for the Moon or on Ganymede because of 2 characteristics. First, the Moon and Ganymede are small ($R = 1700$ and 2600 km respectively) so the heat flow across the core mantle boundary never reaches the critical value required for dynamo action (see Eq.1, Eq.2, Fig. 2). Second, their volumetric metallic fractions are only $1-2\%$ meaning that the impactor needed to differentiate a large volume of metal is unrealistically large. Even the most optimistic cases show that an early lunar dynamo is very unlikely in our models. However, these models do not yet take into account either the latent heat release in the protocore due to metal phase crystallization or radioactive heating of ^{40}K which can lead to a significant increase of the heat flow across the core-mantle boundary. One way to explain Ganymede's current magnetic field is a late giant impact leading separating a large volume of metallic phase. This would require that Ganymede was not fully differentiated before this event just like Callisto [10].

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