Dynamical Mixing of Planetary Cores by Giant Impacts.

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Summary: According to recent studies on high-pressure mineral physics and on orbital dynamics, the cores of terrestrial planets likely develop compositionally stratified structures during their accretion. This structure prohibits early core convection as well as the generation of an early dynamo. In the case of Earth, this may be inconsistent with the presence of an early dynamo as indicated by paleomagnetic studies. In this work, we examine the possibility that the core stratification could have been reset by the Moon-forming impact. Our impact calculations show that the giant impact can provide kinetic energy large enough to mix the stably stratified core. Therefore, the giant impact helps in explaining the presence of Earth's early dynamo. A key factor here is that this is a general model and it is easily applicable to other planetary systems. Thus, this study contributes to understanding the connection between early dynamos and the accretion history of terrestrial planets.

Introduction: The presence of an early dynamo of a terrestrial planet may be closely related to the impact history of the planet. During the planetary accretion stage, a planet experiences a number of collisions with impactors. These impactors melt part of the planetary mantle and deliver their metallic iron to the planetary core. The metallic iron of small impactors (at least up to a few 100 km) would then be dispersed as droplets which experience metal-silicate equilibration during the descent to the metal pond at the base of the molten mantle [1]. The iron then passes through the solid-rich deeper mantle as diapirs without further equilibration. The ratio of the elemental concentrations in the iron core and in the silicate mantle is called the metal-silicate partition coefficient, which depends on the equilibration pressure P_{eq}, temperature T_{eq}, and the oxygen fugacity. As the planet grows, P_{eq} and T_{eq} increase since equilibration occurs in deeper parts of the mantle. Recent studies indicate that the partition coefficients of some light elements, such as Si and O that are expected to be present in the core, increase as P_{eq} and T_{eq} increase [2]. This indicates that more newly delivered iron could be lighter. As a result, the core would develop a compositionally stratified structure. This is not ideal for the generation of an early global magnetic field, which requires thermal or chemical convection within the core. Solidification of the pure iron inner core would help convection by releasing heat and light elements to the liquid part of the core, but at least for Earth, this would have occurred only recently (1Gyr ago, [3]). Therefore, inner core growth cannot explain the presence of the early magnetic field of the Earth (3.5 Gyr ago or possibly earlier [4]).

Here, we examine whether a giant impact can dynamically mix the core and generate a preferable condition for an early dynamo. We perform impact simulations using Smoothed Particle Hydrodynamics (SPH), which is a Lagrangian method that describes a fluid as a collection of spherical particles. We investigate whether the kinetic energy delivered to the core by an impact is large enough to reset the core stratification. In this study, we focus on the Earth as a first step, but this model is easily applicable to other terrestrial planets.

Model: As a first step, we estimate the potential energy of a compositionally stratified core. The extent of core stratification depends on the stochastic accretion history of the planet, therefore it can vary significantly. In this work, we assume a relatively strong stratification based on orbital dynamics calculations [5] to examine an end-member scenario, even though weaker stratification is possible [6]. The potential energy of a stratified core can be approximately written as $\Delta PE = \int 4\pi r^2 (\rho - \rho_{mix}) V(r) dr$ if the properties only depends on the radial distance from the center of the planet, r. Here, ρ is the density of the stratified core, ρ_{mix} is the density of the mixed core, and V is the potential of the core. We assume that the core is made of 88% pure iron mixed with 12% of silicon, although the Earth's core likely has other light elements, such as oxygen, sulfur, and carbon. We formulate an equation of state for this mixed material partly using the equation of state called M-ANEOS. The core is assumed to be isothermal (6000K).

Furthermore, we investigate the extent of the kinetic energy that is available to mix the core. We perform an impact calculation to estimate the extent of core deformation by impact. The deformed core has an excess of the potential energy, which is partly converted to kinetic energy by wave breaking. The fraction of the potential energy that is converted to the kinetic energy varies depending on the circumstances, but typically ~ 0.25 [e.g., 7].

For the impact model, we use conditions for the Moon-forming impact, mainly because this is likely to have been one of the largest and latest impacts the

Earth experienced and therefore it would be a good candidate to reset the core stratification. The details of this impact have been actively debated – the Earth could have been hit by a Mars-sized impactor (the standard model) [8, 9], or a small impactor hit the rapidly rotating Earth (the fast-spinning Earth model) [10], or two half-Earth size objects collided (the sub-Earths model) [11]. In this calculation, we choose the standard impact model because this model provides the most challenging condition to mix the core due to its smaller kinetic energy involved in the impact than the other models. If the core can be mixed in this model, this would be the case in the other impact models as well.

Results & Discussion: An example of the core structure is shown in Figure 1. Upper parts of the core are more enriched in Si and therefore lighter (Figure 1A and [5]). The black and blue lines represent properties of the stratified core and homogeneously mixed core, respectively. The density structures are shown in Figure 1B. The potential energy of the core ΔPE is computed based on the difference in the density structures.

Figure 2 shows a snapshot of our impact simulation. During the impact, the radii of the core and mantle of the planet change up to ~ 16% and 23%, respectively. The excess of the potential energy is computed based on the extent of deformation. The kinetic energy available to mix the core ΔKE is computed as ~ 0.25 of this excess of the potential energy. In this specific case, our preliminary calculation indicates that the kinetic energy ΔKE is larger than ΔPE (ΔPE/ΔKE<0.5), therefore the core stratification can be dynamically mixed. This indicates that even if the deformation of the core and mantle is relatively small, this impact could efficiently mix the core.

The calculation above focuses on Earth, but this model is easily applicable to other terrestrial planets. By clarifying the connection between the impact history of a planet and the state of the core, we may be able to understand why Mars had an ancient magnetic field and Venus, which is similar to Earth, does not have a magnetic field. Needless to say, further calculations with various core structures and impact conditions are needed to generalize our knowledge on these issues.

References: [1] Dahl, T. W. & Stevenson, D. J., 2010, EPSL, 295, 177. [2] Siebert, J. et al., 2013, Science, 339, 1194. [3] Gomi, H. et al., 2013, Phys. Earth Planet. Inter., 224, 88. [4] Tarduno, J. A. et al., 2010, Science, 327, 1238. [5] Jacobson, S. A. et al. 2015, LPSC 46th, 1882. [6] O'Rourke, J. G. and Stevenson, D. J., EPSL, in rev. [7] McEwan, A. D. 1983, J. Fluid Mech., 128, 59. [8] Hartmann, W. K. & Davis, D. R., 1975, Icarus, 24, 504. [9] Cameron, A. G. W. and Ward, W. R. 1976, LPSC 7th, 120. [10] Cuk, M. & Stewart, S. T., 2012, Science, 338, 1047. [11] Canup, R. M. 2012, Science, 338, 1052.

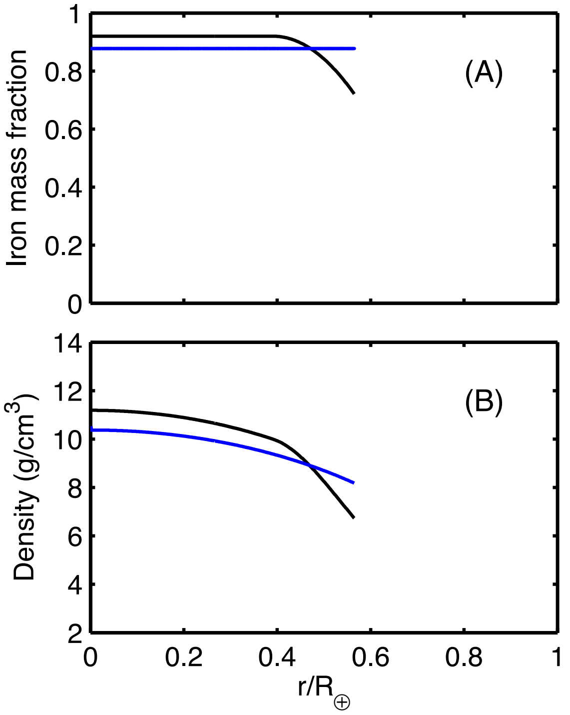

Figure 1: Examples of the core structures. The top panel (A) shows the compositional stratification of the core and the bottom panel (B) shows the core density. The black and blue lines represent the stratified and homogeneous cores.

Figure 2: A snapshot of the standard giant impact. The green and orange colors represent the mantles of the Earth and impactor. The gray and white represent the iron cores of the Earth and impactor, respectively. The white bar represents the current radius of the Earth.