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Constraints for a Solid Lunar Inner Core

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Abstract

Whether or not the Moon has a core and whether or not that core would be fluid, solid or partly solid is still controversial. Recent reanalysis of Apollo seismic data [1] did not only determine the size of the lunar core more accurately but also suggested the presence of a solid inner and a fluid outer core. In order to constrain under which circumstances a solid inner core can form, we calculated a suite of three dimensional thermal evolution models of the Moon, where different parameters were varied. The results show that an inner core can indeed freeze out, assuming the amount of sulphur does not exceed 9 wt%. The observation of an inner core and its size can be used as an indirect constraint on the mantle rheology and composition.

1. Introduction

Various geophysical data have been interpreted to suggest a small core within the Earth's Moon with a radius between 300 km and 400 km. The present state of the core is important in view of the absence of a lunar self-sustained magnetic field and in light of the evidence (not undisputed, however) for an early magnetic field that caused the remanent magnetisation of parts of the lunar crust. In earlier publications [2] we had argued for an entirely fluid lunar core at present as the most straightforward explanation for the lunar magnetic history. Recent reanalysis of Apollo seismic data [1] did not however determine the size of the lunar core more accurately but also suggested the presence of a solid inner and a fluid outer core.

2. Model

In order to constrain under which circumstances a solid inner core can form, we calculated a suite of three dimensional thermal evolution models of the Moon. The lunar mantle was modeled as an internally and bottom heated, isochemical fluid in a spherical shell. The principle of this convection model is widely accepted and is used for thermal evolution models of terrestrial planets [3, 4] We solved the dimensionless hydrodynamical equations of mass, momentum and energy conservation. Assuming the lunar core to consist of iron and some weight percent of a of lighter alloying component a solid inner core forms as soon as the core adiabat intersects with the liquidus temperature of the core alloy. We systematically varied the core thermal parameters and the rheological parameters of the mantle from a dry to a wet rheology and included the thermal effects of a regolith layer.

3. Results

3.1 General Observations

The Earth's Moon is a so-called one-plate-planet, meaning the outer surface is not broken into several tectonic plates but one single rigid shell. The planetary body therefore cools from above by thickening the lithosphere. Since the rigid lithosphere does not take part in the convection anymore, the heat from the interior (core cooling) is transported through the lithosphere by thermal conduction, which is a significantly less effective mechanism of heat transport and hence the lithosphere forms an insulating layer. As a result, the planetary mantle is kept relatively warm. After already 0.7 Ga the core has roughly the temperature of the lower mantle and both cool together during the entire evolution. The dominating heat provider for the mantle is the decay of radioactive heat sources from then on. All presented models have this behaviour in common. However, models with higher surface temperatures have a warmer upper mantle.

3.2 Core Cooling

The beginning of the Moon's thermal evolution is characterized by the formation of large thermal up-

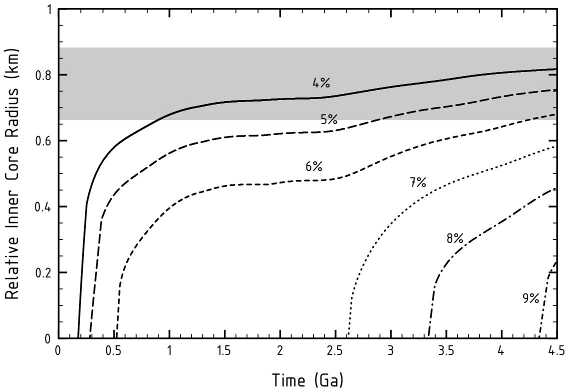

Figure 1: Inner core sizes with ongoing simulation time for a fixed core radius (350 km) and crustal base tempearure (250 K) depending on the sulphur content.

wellings in the mantle. These massive plumes 'draw' heat from the core and cause a rapid decrease of the core-mantle-boundary (CMB) temperature. As soon as the upwellings break down (0.7 Ga) because the CMB has cooled to the same temperature as the lower mantle, core cooling becomes stalled and continues much slower.

3.3 Inner Core Freezing

According to phase of the rapid core cooling within the first 0.7 Ga an inner core starts to freeze out as soon as the core adiabat intersects with the liquidus temperature profile of the core alloy. The onset of core freezing depends on the actual model parameters, where the sulphur content has the largest influence, while core size and crustal base temperature influence the final inner core size relatively little. Figure 1 shows the inner core radii evolution with time for various sulphur concentrations. As soon as iron starts to freeze out latent heat is real eased due to the phase change from liquid to solid. Additionally gravitational energy is released and lost as heat eventually. This caused a heat flow from the core towards the mantle, increasing the CMB temperature and decreasing the cooling of the entire planetary body down. The freezing slows down as the decrease of the CMB temperature is slowed down, too. Furthermore the remaining liquid part of the core becomes more and more iron depleted (or FeS enriched), which causes the liquidus temperature of the core alloy to be shifted to lower temperatures. Henceforth the growing of the inner core becomes slower with ongoing evolution. Our simulations show that the core will freeze out completely after approximately 20 Ga.

3.4 Inner Core Sizes

The inner core size given by [1] is 240 ± 10 km, while the entire core is constrained to the size of 330 ± 20 km. Henceforth, the relative core size ranges between 0.66 and 0.88. All our models with sulphur content below 6 wt% are consistent with this size range (see grey area in Figure 1). The sulphur content suggested by [1] is also less then 6 wt%. As expected the core freezes out earlier for lower amounts of FeS.

4 Conclusion

Our simulations show that the Moon can well have a solid inner core surrounded by a liquid layer. The computed radii for the inner core are consistent with analysis of Apollo seismic data from [1]. The actual choice of the core size as well as the thermal effects of a regolith layer do not have a strong influence on the resulting inner core size. The absence of a present lunar self-sustained magnetic field can be explained by the very slow - if not stalled - growth of the inner core.

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