EVOLUTION OF THE MOON'S CORE IN THE FE-SNOW REGIME. T. Rückriemen[1,2], D. Breuer[1], M. Laneuville[3] and T. Spohn[1,2], [1]German Aerospace Center, Berlin, Germany (tina.rueckriemen@dlr.de, [2]University of Münster, Institute of Planetology, Münster, Germany, [3]Institut de Physique du Globe de Paris, France.

Introduction: Since the Apollo missions it is well known that there is no active magnetic field on the Moon today but its crust shows remnant magnetization [1] suggesting that the Moon experienced a magnetic era between 4.2 and 3.2 Gyr ago with a field strength of some μT [2]. Although various mechanisms have been proposed for the dynamo generation its orgin still remains unanswered. The recent findings of a present-day solid inner core [3] suggest that compositional convection may be responsible for dynamo action in the Moon's core – before that finding compositional convection was in fact disregarded to explain the non-existence of a present self-generated magnetic field [4]. Compositionally driven convection is associated with potential freezing processes. Assuming a core that consists of Fe-FeS, [5] find that core freezing is likely to occur during the Moon's evolution for sulfur concentrations less than ~12 wt.% assuming a dry mantle rheology. The solidification of iron in the Moon's core may either start in the center as for the Earth or at the core-mantle boundary (Fe-snow regime) depending on the sulfur content [6]. A recent study confirms the caveat of compositional convection in the Moon's by solidification starting in the center -- in this case a dynamo would still be active today (LPSC abstract by Laneuville et al.).

In the present study, we examine the evolution of the Moon's core in the Fe-snow regime, where solidification of iron first starts at the core-mantle boundary (CMB). The Fe-snow regime occurs for initial sulfur concentrations higher than $x_s \geq 9$ wt.%. It is initially characterized by a snow zone and a fluid core layer below – the latter convects due to compositional buoyancy. We propose that in the Fe-snow regime the lower fluid core is the origin of the magnetic field – in the snow zone large scale convection and thus dynamo generation is unlikely [7]. Thus, such a dynamo is restricted in time and would stop as soon as the growing snow zone comprises the entire core. To investigate the evolution of the Moon's core in the Fe-snow regime, we apply a 1D thermo-chemical core evolution model treating the Fe-snow process [7], which in turn is coupled to a 1D parameterized convection model to calculate the thermal evolution of mantle and crust [8]. In particular, we study the onset of the Fe-snow and the duration of dynamo action considering that it only lasts till the snow zone comprise the entire core.

Method: The 1D thermo-chemical evolution model of the Moon's core determines temperature, melting temperature, and composition in the core. For the temperature we choose an adiabatic temperature profile as well as a conductive temperature profile. In case of the latter one we also include the release of latent heat (in the snow zone) and the consumption of latent heat (in the deeper entirely liquid core). We calculate the melting temperature via an expression by [9]. Further, we determine a consistent pressure and density profile based on a 3rd order Birch-Murnaghan equation of state and a three-layer structural model [10]. The amount of solidifying iron within the snow zone is calculated by assuming thermo-chemical equilibrium (Lever rule). We further treat the subsequent redistribution of iron to the deeper fluid core. This process includes the continuous depletion of the snow zone in iron and the enrichment of the deeper fluid core in iron (as long as no inner core is present). The thermal evolution model for crust and mantle is calcuated using the parameterized convection model of stagnant lid planets [9].

Results: We study the Fe-snow regime in the Moon's core by varying three parameters: the inital sulfur concentration x_s (9-19 wt.%), the thermal conductivity k_c (20-84 W/mK), the reference mantle viscosity ($\eta \approx 10^{19}$ Pas (wet), $\eta \approx 10^{21}$ Pas (dry)) and the initial mantle temperature (T_m=1560 K (cold), T_m= 1750 K (warm)) with our reference model being x_s=13wt.%, k_c=32 W/mK, $\eta \approx 10^{19}$ Pas, T_m=1560 K. All calculations assume an initial temperature jump across the lower boundary layer of the mantle of about 300 K. The main results of the preliminary study are shown in Figure 1. The general trend for the different parameter variations is the following: With increasing initial sulfur concentrations the dynamo starts later in the Moon's thermal evolution and its duration increases – similar when increasing the reference mantle viscosity and the initial mantle temperature. A variation in the thermal conducitivity of the core has only little impact on start and duration. Figure 1 indicates that within the frame of the present parameter study a dynamo due to Fe-snow in the Moon's core does not match the observed data as suggested by [2]. The parameters either match the starting point of the dynamo or its duration but not both criteria at the same time. Whenever the dynamo duration exceeds a few hundered million years, the starting point of the dynamo is too late (2.5-4 Gyr) in the Moon's evolution. In these cases, for example very low core temperatures that are close to the respective melting temperatures are required to shift the starting

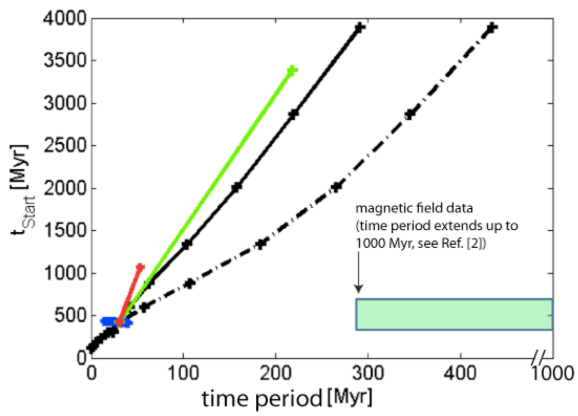

FIG. 1: Results for all parameter variations investigated for the Moon's core in the Fe-snow regime. The y-axis (t_$_{START}$) presents the time, for which the Fe-snow regime starts (0 Myr defines the beginning of the evolution) and the x-axis shows the time period of the growing snow zone unitl it comprises the entire core. The green shaded area marks the suggested starting point and minimal duration of the dynamo (see Ref. [2]). The colored lines refer to the adiabatic core temperature case and to the following parameter variations: blue (thermal conductivity), red (initial mantle temperature), green (mantle viscosity). The black lines correspond to different sulfur concentrations with the dashed-dotted line given for adiabatic core temperature profiles and the solid line for conductive profiles.

point to earlier times. On the other hand, whenever the dynamo starts early in the evolution, the duration of the dynamo is lower than 100 Myr – not consistent with the observations [2]. One possibility to extend the duration of the dynamo would be much slower cooling of the core, which could be achieved by a slow cooling mantle on top of the core. Yet such scenarios have not been tested within the present study and remain an issue for future work.

The present findings further suggest that the limited occurence of a lunar dynamo may be caused by a transition from the classic inner core growth regime to the Fe-snow regime. The scenario would include a lunar core that starts to crystallize in the center thereby starting a chemical dynamo. During inner core growth the outer core becomes enriched in sulfur. Eventually, that enrichment leads to the concurrent start of Fe-snow in the outer core. Since the duration of the Fe-snow regime is rather short (Fig. 1) it could lead to an early shut down of the dynamo, which is not observed within the inner core growth regime. Here we obtain the Fe-snow regime in the Moon's core for sulfur concentrations around 9 wt.%. Assuming a present day Fe-snow regime in the Moon with an outer core sulfur enrichment of 9±1 wt.%, the relative inner core size as a function of different initial S concentrations is shown in Figure 2. Calculations of present-day relative inner core sizes for different initial sulfur concentrations by Laneuville et al. (see companion abstract) show that the transition between the two regimes may only be feasible for initial sulfur concentrations close to 9 wt.%. Thus, if the initial S concentration deviates too much from the transition concentration of 9 wt.% it takes too long to enrich the outer core in enough sulfur .

Conclusion: We find that the Fe-snow regime as the only core solidification process is unlikely to explain the observed data of remant magnetization. Similar, the clasical inner core growth regime is not able explain the non-existence of a present-day field. As an alternative, we suggest that a transition from the inner core growth to the Fe-snow regime may be the key to explaining the lunar magnetic field. Future studies will show if this transition can be explained by thermal evolution models.

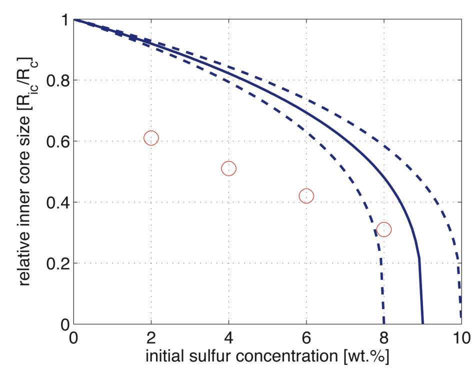

FIG. 2: Different initial sulfur concentrations which relative inner core size must be reached to gain an enrichment of sulfur in the outer core of 9 wt.% (solid line), 8 wt.% (left dashed line) and 10 wt.% (right dashed line). The red dots are calculations of the final relative inner core sizes by Laneuville et al. (see abstract of this LPSC meeting).

References: [1] Wieczorek, M. A. et al. (2006) Reviews in Mineralogy and Geochemistry, 60, 1, pp. 221– 364, [2] Garrick-Bethell et al. (2009), Science, 323(5), 356, [3] Weber, R. C. et al. (2011), Science, 331(6015), 309–312, [4] Konrad, W., and T. Spohn (1997), Advances in Space Research, 19, 1511, [5] Laneuville, M. et al. (2013), JGR, 118, 1435–1452, [6] Williams, Q. (2009), EPSL, 284(3-4), 564–569, [7] Rückriemen et al. (2013), EGU, Vienna, Austria, [8] Grott, M. and Breuer, D. (2008), Icarus 193, pp. 503–515, [9] Buono, A. and Walker, D. (2011), GCA 75, [10] Rivoldini, A., T. et al. (2009), Icarus, 201(1)