THE MOON'S IMPACT HISTORY: RECONSTRUCTION BASED ON HIGHLY SIDEROPHILE ELEMENTS.

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Introduction: The Moon experienced a violent impact history after its formation. Several scenarios [e.g., 1-3] have already been proposed to quantify its impact history, but the details are still under debate. As a consequence of the cosmic bombardment, the impactor material was added to the Moon. In particular, the enrichment in highly siderophile elements (HSEs) in the lunar mantle and crust are considered as a signature of such late accreted material. The HSEs, characterized by strong affinities to metal relative to silicates, are thought to be substantially partitioned into the metallic core of the Moon, leaving the early silicate mantle stripped of HSEs [4]. The late-arriving impactors, containing HSE abundances typical of chondritic meteorites, are thought to have replenished the mantle HSE content after the core formation [4-6]. Upon solidification of the lithosphere and formation of a thick crust, it becomes increaseingly harder for impactor to penetrate into the mantle. As a consequence the exotic material is mixed into the pristine lunar crust [7,8]. Therefore, the HSE concentrations in the crust and mantle provide constraints on the accretion history and differentiation process of the Moon. In this work, we assume the impact flux according to [2] and conduct Monte Carlo (MC) simulations to investigate the impactor mass accreted into the crust and mantle of the Moon during its impact history.

Methods: We use the iSALE [9,10] shock physics code to study the impact cratering process on the spherical Moon. We carried out a suite of impact models: impact velocity: v =10-25 km s^{-1}; impact angle θ =15^{o}-80^{o}; impactor diameter L = 50-630 km. For each model, we calculate the impactor mass added to the Moon. We then conducted a MC routine with the given crater production function [2], and prescribed probabilities of impact velocities [11] and impact angles to calculate the projectile flux and the retention ratio (RR) of impactors with the iSALE modeling results. We varied the start times for the impactor retention, after the Moon formation (T1), in the mantle (T2) and crust (T3) to investigate if the added impactor mass can reproduce the mass of the HSEs in lunar crust and mantle [4-8]. We recorded the impactor mass to the Moon for three time intervals, i.e., T1-T2, T2-T3, and T3-present day.

Results: In contrast to early work [12], we show that the RR depends not only on the impact angle, but also on the projectile size: large projectiles (D > 100 km) escape much easier than small ones. In addition, a very low retention ratio, twice lower than for a 45^{o} (most probable) impact event, is averaged over the total impact flux.

Our MC model results indicate that, for the impact flux of [2], the best start time for the retention of impactor material into the crust and mantle is at 4.15 Ga (T3) and 4.35 Ga (T2), respectively. The modeled impactor retention masses are 0.35×10^{19} kg for 0-4.15 Ga, 1.46×10^{19} kg for 4.15 Ga-4.35 Ga, and 4.85×10^{19} kg for 4.35 Ga-4.50 Ga. These accreted masses agrees well with estimates of accreted mass in the average meteorite-contaminated crust (0.40×10^{19} kg, [8]) and the mantle (1.48×10^{19} kg, [6]) of the Moon, based on HSE abundances in lunar samples. The time of 4.35 Ga for HSEs started to retain in the mantle corresponds to the time when ~80% of the LMO was crystallized [13]. The HSE budget of the crust is indicateive of the impact flux after the crust solidification at 4.15 Ga.

Discussions: In our simulations, the total impactor mass hitting on the Moon is ~ 6.5×10^{-5} $M_{\oplus}$, whick is significantly larger than estimates considered before [3,8]. This mass is ~ 1.3 times larger than the value of 5×10^{-5} $M_{\oplus}$ from the scenario proposed that the planetesimal tail was responsible for the Moon's early bombardment [14]. Note, an impactor retention ratio of 0.5 was considered in these calculations [14]. If considering the average ratio of 0.2 derived in this work, the total impactor mass hitting the Moon from both studies are similar.

The number of certain to uncertain basins (D > 300 km) on the Moon is 40-90 [15-17], whereas our MC model suggests ~ 400 basins in total: ~ 200 within T1-T2, ~ 90 within T2-T3, and ~ 20 within T3-present day. However, this discrepancy can be explained: impacts between T1 and T2 fail to produce long-lasting structures because of the low viscosity of LMO [13] so that structures would have been erased within a short time; basins formed between T2 and T3 may exist for at most ~ 100 Ma [18]. Therefore, only 45-75 basins in total are still visible on the lunar surface and are the only remanents of the much more violent bombardment history than we thought before.

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