OBTAINING HIGHER TARGET MATERIAL PROPORTIONS IN THE GIANT IMPACT BY CHANGING IMPACT PARAMETERS AND IMPACTOR COMPOSITION

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Introduction: The formation of the Earth's moon by a giant impact with a Mars sized body ("Theia") is widely accepted today, explaining the high angular momentum of the Earth-Moon system and the moon's deficiency in iron [1], [2].

Smoothed Particle Hydrodynamics (SPH) simulations of the giant impact performed during the last 25 years (e.g. [3], [4], [5]), show that an impact of Theia with chondritic composition (30wt% iron, 70wt% rock) and an impact angle of 45° at mutual escape velocity, leads to a sufficiently massive proto-lunar disk and the correct angular momentum in the disk. In all these simulations, no more than 20wt% of the moon-forming circumplanetary disc are derived from the terrestrial mantle ($f_T < 0.2$). Therefore, even a small difference in the isotopic composition of Proto-Earth and Theia results in a different isotopic composition of lunar rocks and terrestrial mantle samples.

However, geochemical studies of lunar material showed that the moon is remarkably similar to the Earth's mantle in chromium [6], potassium [7], silicon [8], and most notably in oxygen [9] and $^{182}W/^{184}W$ [10] isotope ratios. The different oxygen isotope compositions of Earth and Moon, Mars, Vesta and the various groups of chondrites imply that large scale isotopic heterogeneities existed in the early solar system, from which we would expect that Earth and Theia acquired different oxygen isotope compositions. As the $^{182}W/^{184}W$-ratio of the mantle of any terrestrial body depends on the timescale of accretion, timing of core formation, tungsten depletion and re-equilibration during core formation [10], it is very unlikely that Earth and Theia independently evolved the same $^{182}W/^{184}W$ ratios. Excluding a Theia of an elemental and isotopic composition nearly identical to the Earth, we are left with only two possibilities: Either the ejected material was thoroughly equilibrated with the bulk Earth in the aftermath of the collision (see [11] for a proposed oxygen re-equilibration). Or, the fraction of material originating from the impactor (Theia) is considerably less than simulations have led to believe so far. In other words, to account for the isotopic signature, the moon must be derived to > 80% from the Earth's mantle, i.e. i.e. $f_T > 0.8$. In the following paragraphs, we will present new simulations in an extended parameter space, trying to increase f_T.

Methods: First we modify the dynamical parameters impact velocity and angle. Second, we investigate the influence of a non-chondritic impactor composition, by considering ice- and iron-rich impactors. All simulations were performed with the SPH & self-gravity code SPHLATCH using the ANEOS equation of state and a resolution of 500'000 particles.

In the ice-enriched impactor scenario, we model the impactor as an object having the assumed composition of solids beyond the snow line of the early solar system (50wt% water ice, 38wt% rock, 12wt% iron, fully differentiated). An interesting aspect of icy impactors is that the ice is largely vaporized and might be relatively easily lost through thermal escape later on. A similar proposal was recently put forward by [12].

The second non-chondritic impactor considered here is an iron-enhanced impactor similar to the planet Mercury (30wt% rock, 70%wt iron, fully differentiated). Recent models [13] of planetesimal disk evolution suggest, that the population of the second-largest bodies should be mantle-stripped due to encountering collisions well above their own escape velocity. Both non-chondritic cases are modeled for the first time.

Results: The largest increase in f_T is reached by the modification of the impact angle and velocity. Using the same parameters with a non-chondritic composition of the impactor lowers again f_T.

A more head-on collision, allows a higher impact velocity for the same final Earth-Moon angular momentum (1 lem). With impact velocities above the escape velocity, it is easier to put mantle material into orbit. Figure 1 shows snapshots of a head-on impact with 30° angle and 1.30 v_{esc} velocity. Large amounts of mantle material are put into ballistic orbits. Tidal forces circularizing the orbits are less effective, compared to the canonical case [4], so that the material enters more eccentric orbits. Part of it re-enters later inside the Roche limit (green circle), where it is sheared and circularized into the disk. The final mass of the disk is lower than in the canonical case and very sensitive to the initial conditions, as the number of clumps having just the right orbit to not be re-accreted or ejected depends critically from the way the initially ejected arm of material accretes into clumps. It has been shown in previous SPH simulations [14], that this also depends on the numerical resolution.

How much of which material ends up in the proto-lunar disk is partly determined by the impact geometry, in particular how deep the impactor plows through the target mantle, and therefore also the density of the impactor. Figure 2 shows snapshots of four different models just after impact. In the canonical case

(Fig. 2, top left), most of the disk material originates from the warped mantle of the impactor. More head-on collisions lessen this effect (Fig. 2, top right).

The head-on, ice-enriched model (Fig. 2, lower right panel) is less efficient than the chondritic head-on case, but nevertheless increases f_T, compared to the canonical case.

Scenarios where the impactor has a large iron core (Fig. 2, lower left panel) are also less efficient compared to the chondritic case, but with the side effect of a large addition of iron to the inner disk. Interestingly, the mixture of limited amounts of impactor-derived iron metal (~4%) and Fe^{3+}-rich [15] silicate material derived from the Proto-Earth's deep mantle (~80%) could also possibly explain the observed FeO-enrichement of the moon (13%wt FeO) relative to the terrestrial mantle (8%wt FeO), via the process of reverse iron disporportionation under decompression ($Fe + 2 Fe_2O_3 = 3 FeO$). However, for this scenario to work, it is crucial that the majority of the iron-rich inner part of the disc re-accretes with the Earth.

Conclusions: More head-on impacts can increase the proportion of terrestrial mantle derived material (f_T) in the moon-forming disc, but it is also harder to match the disk mass and the overall angular momentum of the bound material compared to the canonical case. Assuming a non-chondritic composition of the impactor does not change this result. The most promising case is a 30° impact angle collision with about 0.2 M_{Earth} and 1.30 v_{esc}, leading to a disk of roughly lunar mass with $f_T = 0.6$. Disk masses can be expected to increase with higher resolution, as artificially high numerical viscosity overestimates the amount of material re-impacting on the second encounter with the target body. Other cases (e.g. $M_{imp} = 0.15 M_{earth}$, 40° , $v_{imp} = 1.1 v_{esc}$) lead to higher disk masses (1.5 M_{lun}) but have a lower $f_T = 0.53$.

This work shows that by opening up the parameter space, models might be found which satisfy the geochemical constraints, although we have yet to find a model fully explaining the isotopic similarity of the Earth's mantle and the Moon.

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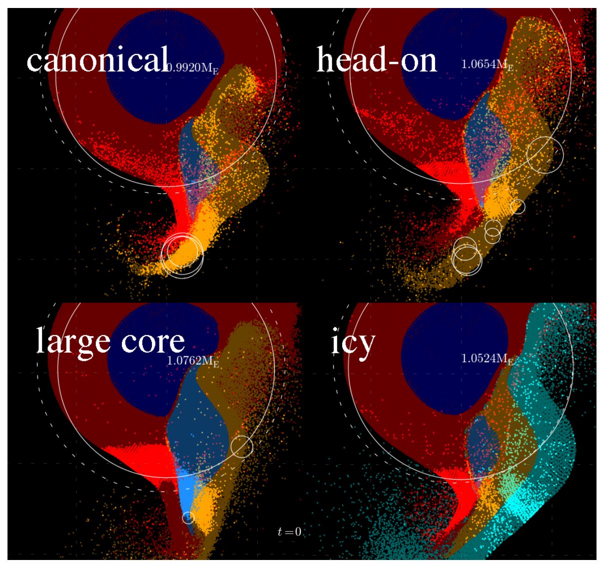

Fig 2: Snapshots half a collisional timescale after impact. Bright colors indicate the material ending up in a proto-lunar disk for different models. Turquoise color in the icy model depicts water ice.

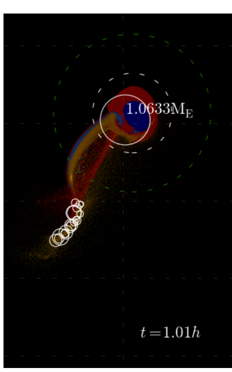

Fig 1: Snapshots of a giant impact of an 0.2M_E impactor with 1.30 v_{esc} impact velocity under an angle of 30° at 1h (left panel) and 6h (right) after impact. About 60% of the rock originates from the target, the final bound angular momentum is around 1.2 lem. Red and orange depict target and impator rock, light and deep blue the respective iron cores. Large clumps of target material get into highly eccentric orbits around the proto-Earth.