WHEN MOONS COLLIDE – SURFACE MIXING AND THERMAL STATE.

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Summary: Earth's Moon shows indications that it may have resulted from a merger of several smaller moonlets [1,2,3]. We perform Smoothed Particle Hydrodynamic (SPH) impact simulations of two orbiting moonlets inside the planetary gravitational potential and find that the classical outcome of two bodies in free space is altered as erosive mass loss is more significant with decreasing distance to the planet. Moreover, for accretionary collisions, impact angular momentum enhances mixing but in the hit-and-run regime, only small amounts of material are transferred between the bodies therefore mixing is limited. Overall, moonlet collisions can impart enough energy to melt ~5-40% of the mantle extending the duration of the magma ocean phase of the final Moon.

Introduction: Impacts between two orbiting satellites is a natural consequence of Moon formation. Mergers between moonlets is especially important for the newly proposed multiple-impact hypothesis as these moonlets formed from different debris disks and merge together to form the final Moon [3]. However, this process is relevant also for the canonical giant impact, as previous work shows that multiple moonlets can form from the same debris disk [1,4].

Satellite pairs were found to be mostly unstable, leading to moon-moon collisions or the loss of one (or both) of the moonlets [5,6]. In the context of the canonical giant impact, where two moonlets are accreted in the same debris disk, high percentage of moonlet merger was found for cases in which the inner moonlet is larger, hence tidally evolves faster than the outer moonlet [5]. In the context of the multiple impact hypothesis, Citron et al. (2017) [6] demonstrated that a preexisting moonlet can remain stable during subsequent impacts onto the protoplanet and later merge with the newly accreted moonlets. While these studies were able to evaluate the dynamical evolution of the two moonlets up to their impact, they do not consider the impact outcome, but rather assume perfect merger of the two components. However, the collisional outcomes vary substantially from perfect merger of the two colliding bodies at low velocities, through partial accretion and erosive interactions, to hit-and-run where the two bodies graze each other but have sufficient relative velocity to escape the mutual gravitational well [7]. In the hit-and-run regime little mass is transferred between the two colliding bodies.

The dynamics of impacts between two orbiting bodies is substantially different from previously heavily studied planetary-sized impacts [8,9,10,2]. Firstly, the impact velocities are smaller and typically limited to ~1 km/sec, thus heating is limited. Secondly, both fragments have similar mass, therefore they contribute similarly and substantially to the final satellite, as opposed to the planetary-scale impacts that were thoroughly studied in the context of the Moon formation [8,9,2]. Thirdly, this process can be more erosive than planetary impacts as the velocity of ejected material required to reach the mutual Hill sphere is smaller than the gravitational escape velocity (V_{esc}), altering the merger efficiency.

In this work we use hydrodynamic calculations to estimate the merger efficiency of these impacts. The impacts occur inside the planetary gravitational potential therefore tidal forces will alter the amount of mass that remains in the final moon. Previous simulations show that moonlets inherit different isotopic signatures from their primordial debris disk, depending on the parameters of the collision with the planet [3]. Here we estimate the amount of mixing between the two colliding moonlets in order to estimate the lunar heterogeneity [11]. The leading theory of the formation of the lunar anorthositic crust is the floatation of plagioclase minerals from a 1000 km-deep lunar magma ocean [12]. Moreover, gravity data from GRAIL reveal igneous intrusions that provide evidence for a lunar radial expansion consistent with a solidification of a 200-300 km-deep magma ocean [13]. We seek to estimate the typical amount of melting due to moonlet collisions and evaluate their potential contribution to the lunar magma ocean.

Results: For non-grazing impacts, erosion is enhanced because the Hill radius of the moonlet increases with the distance to the planet. Therefore, ejected material requires less energy to escape the gravitational pull of the moonlet and typical merger efficiencies close to the Roche limit are lower as energy of the impact increases. Moreover, for grazing impacts, one of the moonlets can be lost as its post-impact orbit enters the planet's Roche limit. Therefore in both grazing and non-grazing cases the merger efficiency is lower near the Roche limit and erosion of the moonlet is enhanced.

Surface Mixing. Perfect mergers with low velocity can construct a somewhat heterogeneous surface ($f_{non-mixed}$>0.5; light markers in Figure 1), because energy is insufficient to mix the material. Non-grazing and higher energy impacts have a well mixed surface ($f_{non-mixed}$<0.2; dark markers in Figure 1), even if the impacts components are not equal. Hit-and-runs impacts, that experienced only one impact, are not well mixed as little mass is transferred by the impact ($f_{non-mixed}$>0.5). The surface mixing is enhanced when the interaction proceeds with subsequent impacts and re-accretion of debris onto the surface, such is the case for the sequence of two hit-and-runs shown for the case in Figure 2. For highly erosive impacts or for cases where one moonlet is disrupted due to continuous passage through the planetary Roche limit, large amount of debris is generated and can later reaccrete on the surface of the surviving moonlet. Therefore a full dynamical evolution is required in order to estimate more accurately surface mixing.

Melting. We consider that material has melted at the end of the simulation if the entropy gain of the SPH particle exceeds the entropy required for melting (ΔS_{melt} ~ $623 \cdot 10^4$ erg $K^{-1} g^{-1}$) [14]. This is a lower boundary for total amount of melt generated during the impact, as moonlets may not be fully solidified before the impact.

Because the impacting velocities are small (~1 km/sec) the melting due to the impact are limited but, as seen in Figure 2 most of the added melt in the impact results from bringing deep inner magma to the surface. High energy accretionary impacts can melt ~40% of the mantle of the final moon, corresponding to ~300 km-deep magma ocean (assuming that all the melt is concentrated at the top layers of the moon). On the other hand, hit-and-run impacts will result in <10% melt, corresponding to <100 km-deep magma ocean. Typical accretionary impacts alone can create enough melt in order to reproduce the required magma ocean depth.

As discussed before, in some cases we observed sequences of hit-and-run impacts because the impacting bodies remain on close orbits after impact. At the end of the simulation the melt in the simulation shown in Figure 2 is roughly homogeneously distributed, and most of the surface is melted. Each impact in this case added a ~10% melt to the mantle of the surviving moonlet. Sequences of hit-and-run impacts do not transfer substantial mass between the impacts, but they can provide an additional heating source to the lunar magma ocean. Therefore, even though the multiple impact scenario produces colder components, these impacts can provide tens of percent of melt to the mantle.

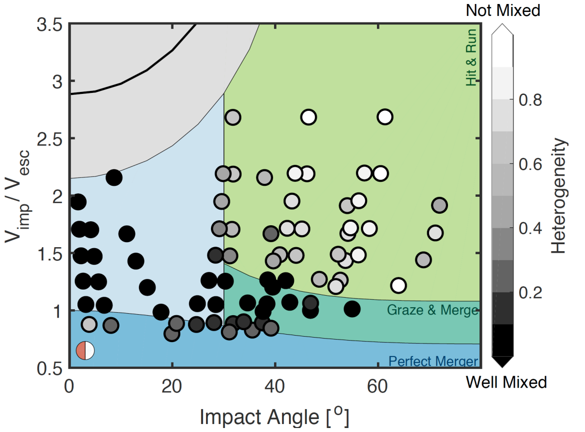

Figure 1 - Colors represent the overall heterogeneity ($f_{non-mixed}$), defined by the fraction of particles that have more than 75% of their neighbors sourced from the same body. The initial mass ratio of the largest impacting moonlet is depicted by the orange pie chart in the lower left corner. The different regions of the plot represent different impacting regimes previously defined by Leinhardt and Stewart (2012) [7] for two bodies in free space.

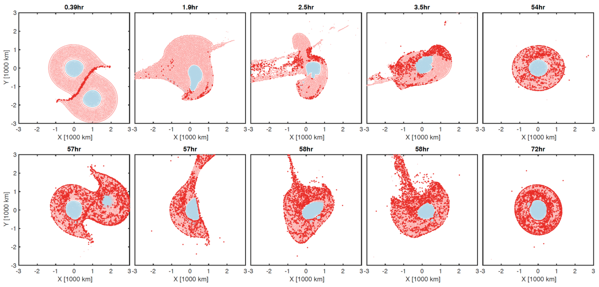

Figure 2 - Sequence of snapshots from two colliding half moons at a distance of $1.5 R_{Roche}$ from the planet (impact angle = 40°; impact velocity = 1.66 V_{esc}). The moonlets impacted twice where both impacts are classified as hit-and-run. The snapshots show a slice of thickness 100 km centered in the center of mass of the surviving moonlet. The light blue particles represent iron material and light/dark shades of red represent the unmelted/melted magma material, respectively.

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