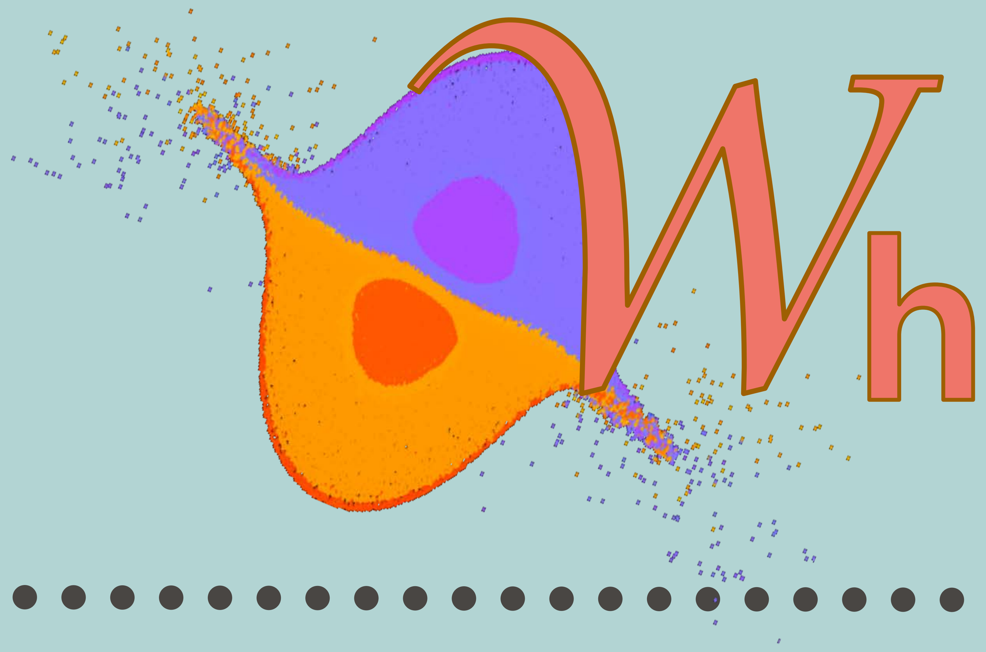

When Moons Collide

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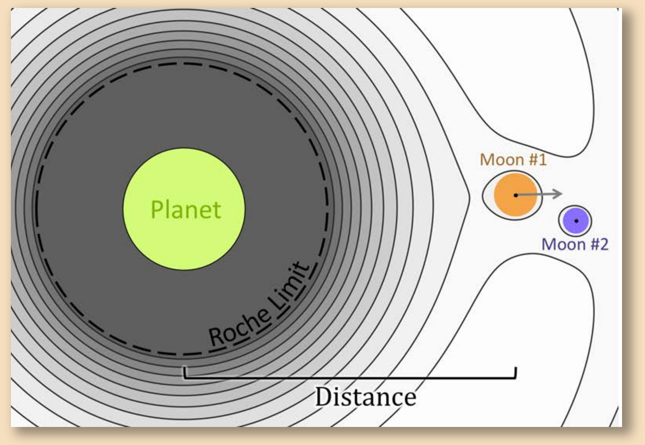
INTRODUCTION

Impacts between two orbiting satellites are a **natural consequence** of Moon formation [1,2,3]. Mergers between moonlets are especially interesting for the newly proposed multiple-impact hypothesis as these moonlets form 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].

In this work we use Smoothed Particle Hydrodynamic code to estimate the **merger efficiency** of these impacts. The impacts occur within the planetary gravitational potential, therefore tidal forces alter the amount of mass that comprises the final moon. In order to directly compare our results with the standard impacts of two bodies in free space we perform reference simulations with no central potential.

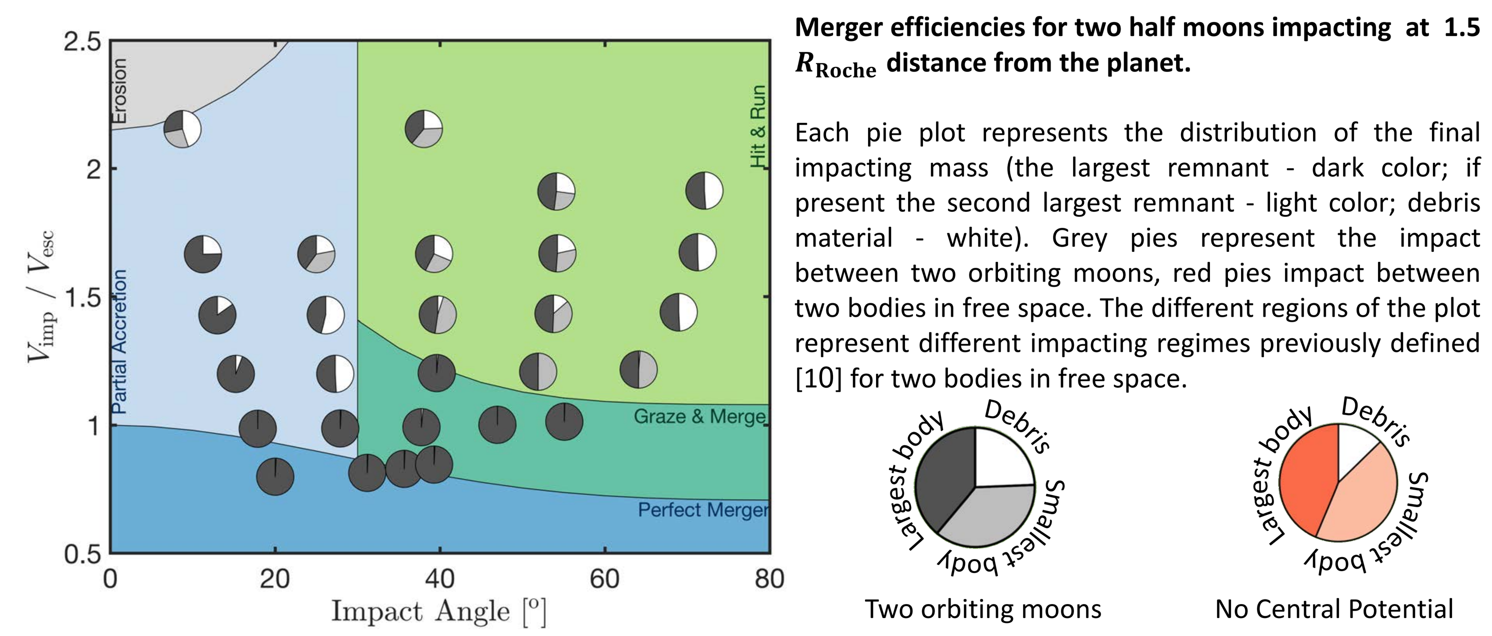


Previous simulations show that primordial debris disks and their accreted moonlets have different isotopic signatures, depending on the parameters of the collision with the planet [3]. Here we measure the **amount of mixing** between the two colliding moons in order to estimate the lunar heterogeneity [5].

The leading theory of the formation of the lunar anorthositic crust is the floatation of plagioclase minerals from a lunar magma ocean [8]. Moreover, gravity data from GRAIL reveal igneous intrusions that provide evidence for lunar radial expansion, consistent with a solidification of a 200-300 km-deep magma ocean [9]. Here we constrain the **amount of melting** in moonlet impacts in order to estimate the contribution to the lunar magma ocean.

- **How are moonlet collisions in a central planetary potential different?**
- **Do merged moonlets preserved heterogeneity?**
- **Are moonlet collisions consistent with the observed anorthositic crust?**

MASS EFFICIENCY

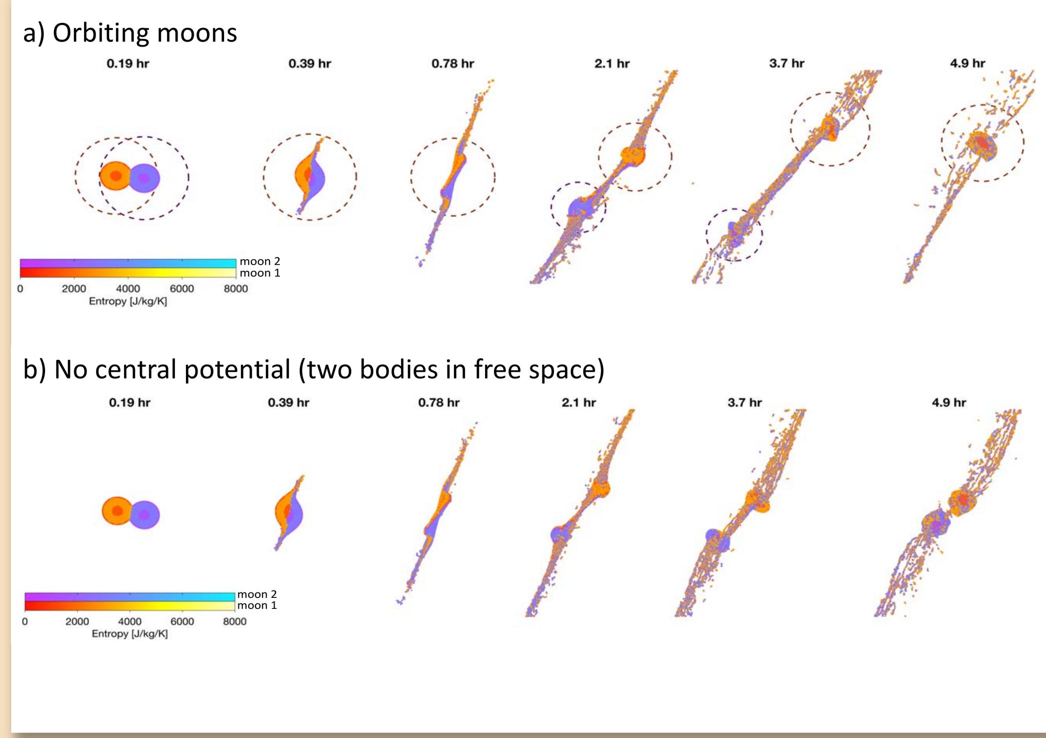


Merger efficiencies for two half moons impacting at 1.5 R_{Roche} distance from the planet.

Each pie plot represents the distribution of the final impacting mass (the largest remnant - dark color; if present the second largest remnant - light color; debris material - white). Grey pies represent the impact between two orbiting moons, red pies impact between two bodies in free space. The different regions of the plot represent different impacting regimes previously defined [10] for two bodies in free space.

- **Impacts in central potential promote moonlet loss.**
- **Moonlet erosion and debris generation are enhanced.**

HIT-AND-RUN



Differences between impacts with and without the central potential.

Several snapshots with similar initial conditions ($\beta = 8^o$; $V_{imp} = 2.15V_{esc}$) of **a)** two orbiting moons inside the planetary gravitational potential; **b)** two bodies in free space. The different color bars represent the entropy of the material originating from different moonlets. All projections are on the equatorial plane with one hemisphere removed. The hill sphere of each orbiting moon is represented by the dashed lines. For simplicity, only material with density of $\rho > 3\ gr/cm^3$ is shown.

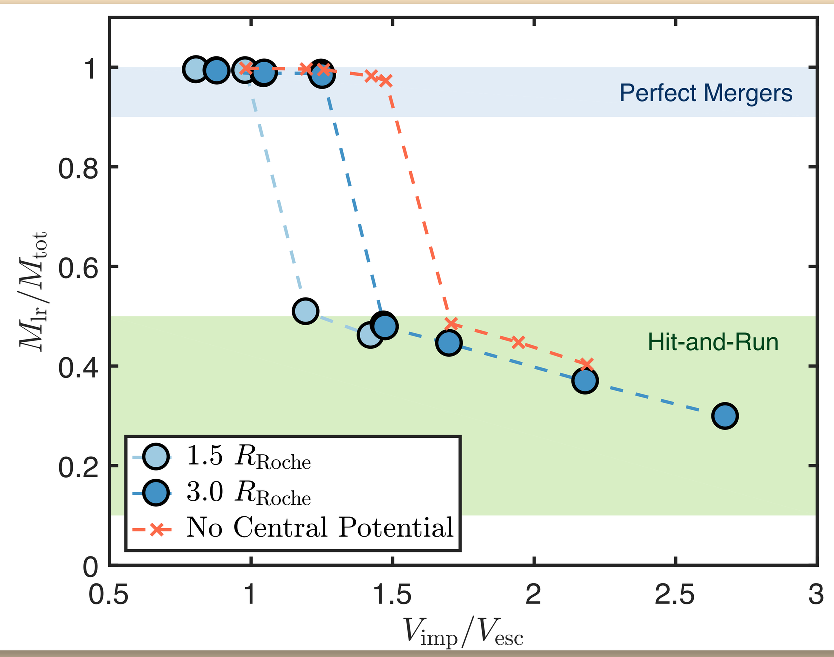
Full movie

- **Hit-and-run impacts are more abundant within a central potential.**

Mass of largest remnant post impact.

Normalized mass of largest remnant vs. impact velocity normalized by the mutual escape velocity for impact angles of $\beta = 30^o$. Circle markers represent moonlet impacts at different distances from the planet whereas the crosses represent impacts without the gravitational potential of the planet.

Example

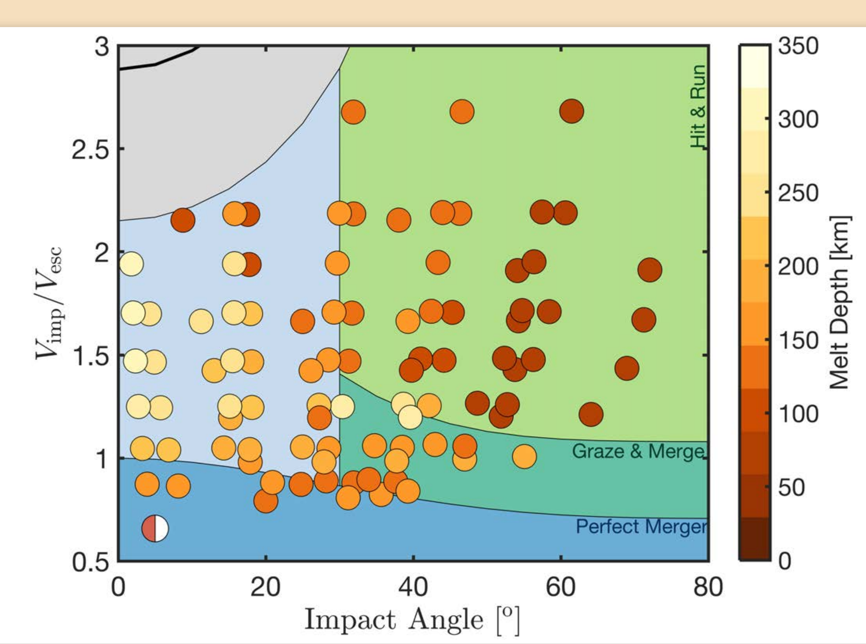


- **Transition to Hit-and-run regime occurs at lower velocities closer to the planet (deeper in the potential well).**
- **Hit-and run impacts transfer small amount of angular momentum, the orbits are only modestly perturbed, therefore expect sequences of hit and runs.**

THERMAL STATE

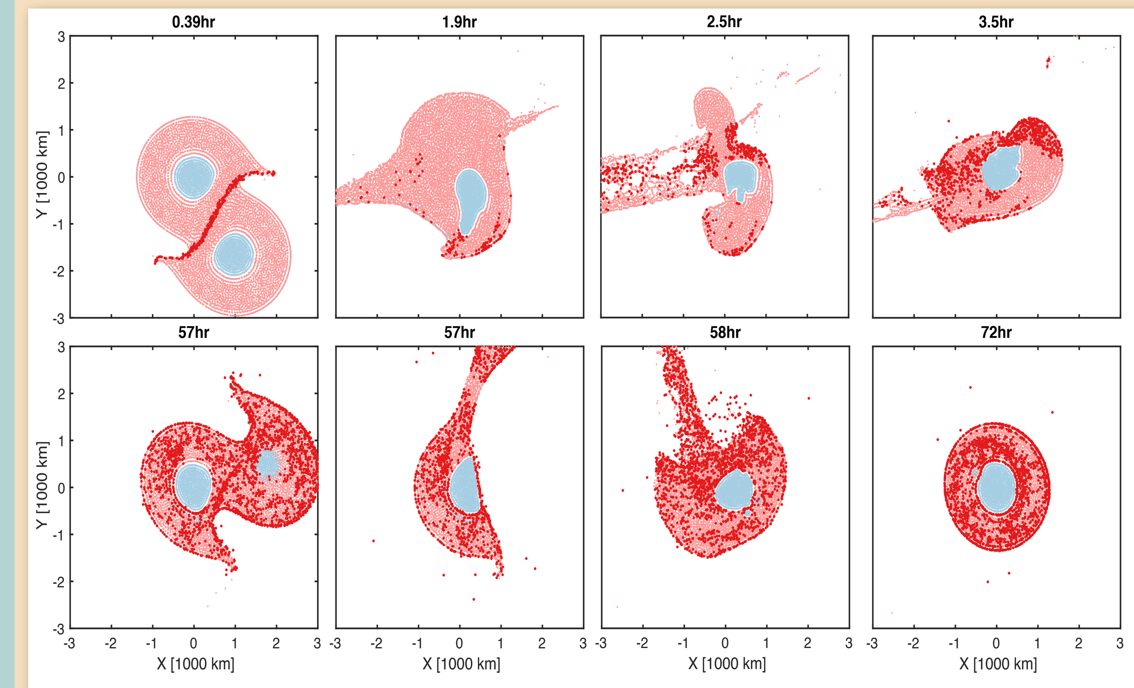
Depth of magma ocean expected for two half-moons impacting.

Colors represent the overall magma-ocean-depth, assuming that the melt is homogeneously distributed on the top layers of the moonlet. The different regions of the plot represent different impacting regimes previously defined [10] for two bodies in free space.



- **Magma ocean (100's km) & anorthositic crust growth is expected**

THERMAL STATE cont.



Sequences of two hit-and-run impacts – thermal evolution.

Snapshots from two colliding half moons at a distance of $1.5\ R_{Roche}$ from the planet ($\beta = 40^o$; $V_{imp} = 1.66V_{esc}$). The moons impacted twice where both impacts registered are hit-and-runs. The snapshots show a slice of 100 km around the center of mass of the surviving moon. The blue particles represent iron material and light/dark red represents the unmelted/melted magma material.

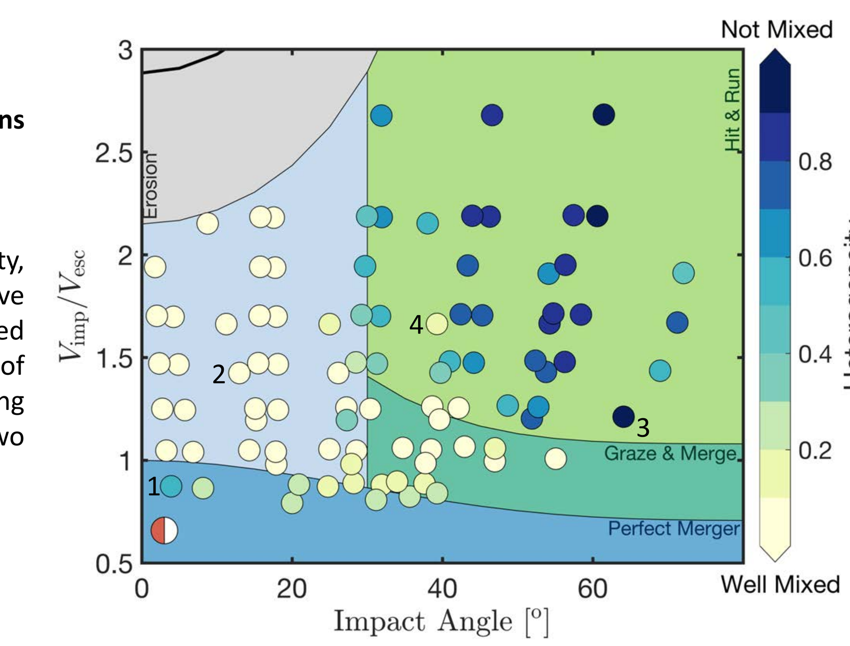
Full movie

- **Interaction of bodies of comparable size enables deeply sourced mantle to rise to the surface, decompress and melt.**
- **Sequences of impacts generate additional melt.**

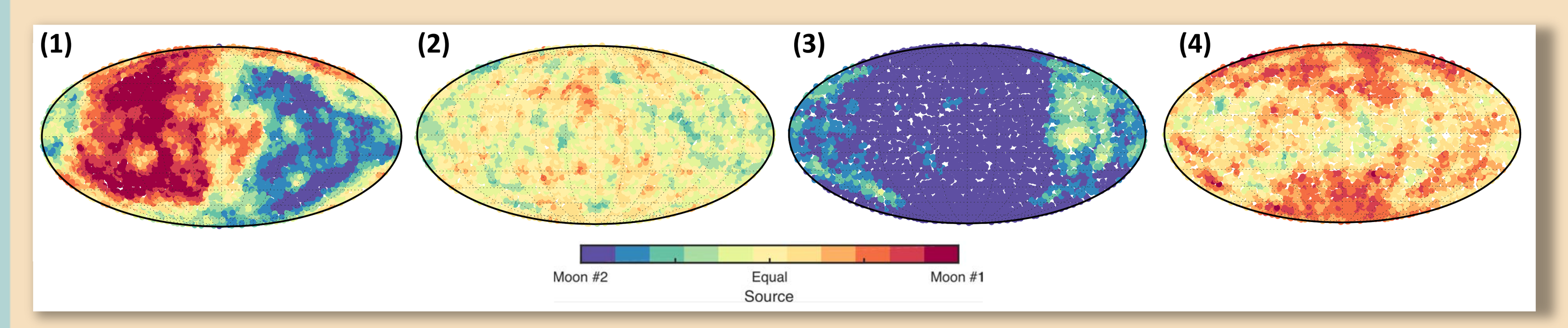
SURFACE MIXING

Surface mixing for two half-moons impacting.

Colors represent the overall heterogeneity, defined by the fraction of particles that have more than 75% of their neighbors sourced from the same body. The different regions of the plot represent different impacting regimes previously defined [10] for two bodies in free space.



- **(1) Low velocity, head-on impact – not enough angular momentum for efficient mixing.**
- **(2) More typical accretionary impacts are well mixed.**
- **(3) Hit-and-run impacts can create a heterogeneous surface.**
- **(4) However, sequences of hit-and-run impacts enhance mixing.**



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[1] Ida S. et. al. (1997) *Nature, 389,* 353–357. [2] Jutzi M. and Asphaug E. (2011), *Nature*, 476, 69-72. [3] Rufu R. et. al. (2017), *Nature Geoscience,* 10, 89-94. [4] Salmon J. and Canup R. (2012), *ApJ*, 760:83. [5] Robinson L. K. et. al. (2016), *Gca,* 199, 244-260. [6] Canup R. et.al. (1999), *ApJ*, 117, 603-620. [7] Citron R. et. al. (2017), *DPS*, 508.05. [8] Elkins-Tanton L. T. et. al. (2011), *EpsL*, 304, 326-336. [9] Andrews-Hanna J. C. (2014), *Nature,* 514, 68-71. [10] Leinhardth Z. M. and Stewart S.T. (2012), *ApJ,* 745:79.