The Lunar Farside Highlands as the Late Accretion of the Moon's Companion.
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Summary: The most immediate geological feature of the Moon is the terrain and elevation dichotomy, with the nearside being low, flat and dark, and the farside old and mountainous. Associated with this geological dichotomy is a compositional and thermal variation, with the nearside Procellarum KREEP Terrane (PKT) and environs interpreted as having thinner, compositionally evolved crust compared to the feldspathic highlands, and higher heat flow. We explore the origin of the lunar dichotomy as a late carapace added by the accretion of a companion moon.

Two moons could be stable about the Earth for tens of millions of years or more, depending on such factors as the original orbits of both bodies (presumably both formed in the same giant impact), the spin state of the early Earth, and the tidal evolution. Collision by a companion moon has been considered [1] to form the SPA basin in a low velocity collision. We show that the collision by a very massive companion moon forms an accretionary pile [e.g. 2] rather than a crater.

Initial Conditions: We regard the origin and dynamics of two moons as a separable problem, and focus here upon the physical properties that are required by an impact that might form a 'pasted on' farside highlands. The size of the companion moon is easy to estimate: it must be massive enough to add ~50 km to the topography if accreted primarily onto one hemisphere, thus ~1300 km diameter. As for composition, to first order the impacting moon would be of bulk composition similar to that of the Moon. But some (possibly major) compositional differences might result from the 'hit and almost run' collision [3] and the poorly understood evolution of the protolunar disk.

Given the scale of the collision, the pressure forces overwhelm the rheological stresses (strength, viscosity). Rheology and thermal state are important considerations for the long term fate of the emplaced material, but are also regarded as separable problems. Our focus is on the initial emplacement of material in the hours following a moon-Moon collision.

Approach: We use the SPH code of [4, 5] which was extended by [6] to include porous materials. Recently we also implemented [7] a model for dense granular flow based on the rheology suggested by [8]. We compute self-gravity using a grid-based gravity solver. The simulations below use non-porous bodies and a granular rheology with particle sizes of d = 5 km is used to model both target (crust and mantle) and projectile. It is important to note that similar results are obtained using a liquid rheology.

We model the Moon as a 3500 km diameter sphere with 700 km iron core. The companion moon is modeled as a 1270 km diameter sphere of basalt colliding at 2 km/s at impact angles 30°, 45°, 60° and 85°, where 90° is grazing. Both target and projectile have evolved to hydrostatic equilibrium before the collision. We use the Tillotson equation of state for iron (the core) and basalt (the mantle, crust, and companion moon). Our preliminary simulations use 0.8 million SPH particles for a spatial resolution h ~ 30 km, so the initial crust (assumed 30 km globally before the collision) is not resolved as a separated material, but only as particles tracked during the simulation. Ongoing higher resolution simulations (h < 15 km) model the crust explicitly.

Simulation Outcome: A companion moon ~1/3 the diameter of the Moon striking at subsonic (2 km/s) velocity does not form a crater. Most of the colliding material stays local to the impact (**Figure 1**), pasting on a thickened crust and forming a mountainous region comparable in extent to the farside highlands.

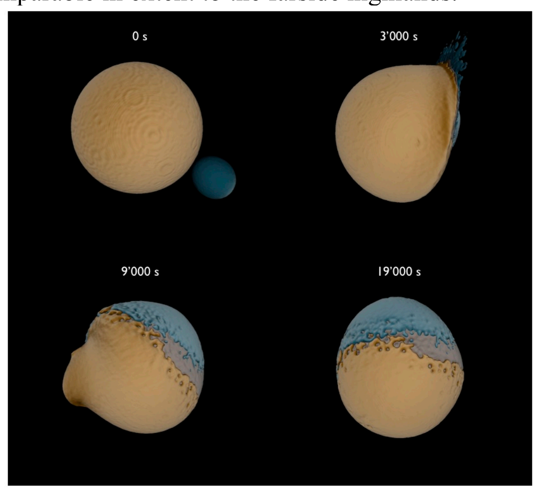

Figure 1: Snapshots of the simulation of a 2 km/s, 60° impact of a 1270 km projectile on the moon. The colors show the projectile (blue), the initial crust (brown) and the mantle (black).

Although our preliminary modeling serves as a concept demonstration pending the more detailed results, a quantitative comparison with today's Moon is possible. It is challenging for three reasons: (1) the reported lunar crustal thickness [9] is dependent on parameters for crust and mantle density; (2) the SPH model is at the limits of the required resolution; and (3) we ignore any post-impact diffusion of topography, either longer term by tidal/thermal evolution, or short term by melt flow or fluidization. Impact melting is not important at these velocities, but if the collision happened within the first ~50 Ma a lunar magma ocean would influence the outcome. If the collision happened within the first ~10 Ma there would be melts expected inside the projectile. These details do not change the outcome of the SPH model, which gives similar result for various rheologies (liquid; granular), but they require us to look beyond the post-impact state to later evolution.

Topographic Comparison: To reduce ambiguity in crustal density assumptions, our goal is to compare the outcome of the simulation directly to the measured Bouguer gravity anomaly. For now we compute the post-collision crustal thickness, for comparison with [9], by considering both the old crust (presumably 30 km initial thickness; it gets partly removed/redistributed) and the projectile material which is accreted on top (treated simply as new crust).

Looking at post-collision simulation results and the present Moon shows some major differences. Notably, the crustal thickness variation obtained from this simulation (~0-150 km) is perhaps twice the present variation. **Figure 2** shows the crustal thickness resulting from this analysis for the case of the 60° impact, in comparison with the crustal thickness data/model by [9]. A profile of the crustal thickness produced in our model is plotted in **Figure 3**, for one latitude. In the impacted hemisphere our simulation result can be very well fitted by a degree-2 Legendre polynomial. Garrick-Bethell et al. [10] interpret this degree-2 structure as evidence for spatial variation in tidal heating. The nearside then requires a second major event or process of crustal thinning. Our model results in degree-2 terrain only on the impacted hemisphere, in accordance with the observations. It also provides a plausible mechanism for enhanced heat flow (maria) when colder impactor material forms a lid on top of the impacted hemisphere, altering the global heat flow.

Future Work: This initial modeling is a concept study because the simulations only marginally resolve the crust and do not include compositional variation within the projectile or between the mantle and the crust. Nor have we tuned the initial conditions to try to achieve a better match. A suite of higher fidelity simulations will be presented at the meeting.

References: [1] P. H. Schultz, LPSC abstract, p. 259, 1997. [2] M. J. S. Belton et al., Icarus 191, 573-585 (2007) [3] E. Asphaug, Chemie der Erde, 70:199, 2010 [4] W. Benz and E. Asphaug. Icarus, 107:98, 1994. [5] W. Benz and E. Asphaug. Computer Physics Communications, 87:253, 1995. [6] M. Jutzi, W. Benz and P. Michel. Icarus, 198:242, 2008. [7] M. Jutzi, E. Asphaug, GRL, in press. [8] P. Jop, Y. Forterre, and O. Pouliquen. Nature, 441:727, 2006. [9] M. A. Wieczorek, et al., Reviews Mineralogy & Geochemistry, 60:221, 2006 [10] I. Garrick-Bethell, F. Nimmo, M. A. Wieczorek, Science, 330:949, 2010

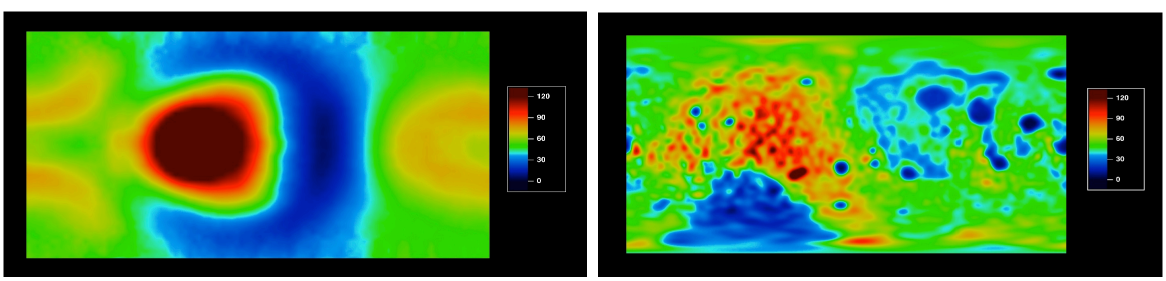

Figure 2: Left: Crustal thickness (in km) after a 2 km/s, 60 degree impact of a 1270 km projectile (coming from the right) as a function of longitude (-180° to 180°) and latitude (-90° to 90°). The red material is mostly projectile. The impact can have had any geometry, since the Moon would have realigned. Right: Comparison data set by [9]; blue at bottom is the SPA basin. The lunar far-side is left of the center.

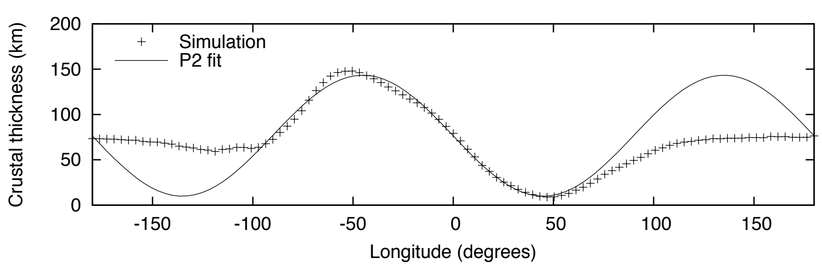

Figure 3: Crustal thickness profile computed at a latitude of 18° along the longitudinal direction. Also shown is a degree-2 Legendre polynomial (P2), fitted to the crustal thickness profile between -100° and +50°; see [10].