GIANT IMPACT OUTCOMES ARE DEPENDENT ON SCALE AND DENSITY STRATIFICATION. T. S. J. Gabriel[1], Jackson, A.P.[2], Asphaug, E.[3], [1]Arizona State University, 781 E Terrace Mall, ISTB4, Room 795, Tempe, AZ 85287-6004, [2] Center for Planetary Sciences, University of Toronto, [3] Lunar and Planetary Laboratory, University of Arizona, (Travis.Gabriel@asu.edu).

Introduction: The final orbital and compositional configuration of the terrestrial planets is strongly governed by giant impact events. These collisions occur between large, similar-sized planetary 'embryos' and feature a rich array of outcomes not exhibited by cratering events between disparately-sized bodies. One example is 'hit and run,' where the impactor plows through the target, continuing downrange largely unscathed [1]. Unlike in cratering collisions, the material strength of the bodies is negligible in comparison to gravitational (tidal) forces that act to disrupt and redistribute mass during the collision [2].

Smoothed Particle Hydrodynamics (SPH) codes are employed to simulate giant impacts to understand the relation of pre-impact conditions to post-impact outcomes. When building scaling laws (pseudo-models) of giant impact outcomes in the gravity regime several assumptions are made:

1. **Scale Invariance:** The mass of remnants is invariant of the scale of the collision [2,3].
2. **Material Invariance:** The mass of remnants is invariant of the material composition of the colliding bodies [3,4].

By analyzing ~1400 SPH simulations, we demonstrate that these common assumptions are likely invalid. We also demonstrate that the threshold for hit and run [5] often employed in N-body planet formation simulations [*e.g.* 6,7] underestimates the occurrence of hit and run. Our results have significant implications for the phenomenology of giant impacts through different stages of the chaotic phases of planet formation.

Methodology: We analyze ~1400 SPH simulations that include collisions of bodies with different materials: rocky (pure SiO_2), 'chondritic' (2-layer; 70% SiO_2, 30% Fe), and icy (3-layer; 50% H_2O, 35% SiO_2, 15% Fe). Pre-impact conditions range from 1-4 v_{esc}, with fine sampling at more probable, low velocities (~1-2 v_{esc}) [*e.g.* 6]. We sample the entire range of possible impact angles, from $0.1° < \theta_{imp} < 89.5°$.

We develop an empirical model to fit the results from these simulations in terms of the remnant masses; best-fit parameters were optimized [8] using a Markov-chain Monte Carlo routine [9]. We implement a weighted scheme that accounts for imbalances in the simulation database, *e.g.* weighting simulations by the expected distribution of impact angles [10]. The empirical model can be implemented in an N-body environment, encouraging the quick adaptation of these results in planet formation codes.

Results: We find our disruption thresholds across the database of simulations are systematically lower than those reported in [3]. Specifically, for head-on collisions we find catastrophic disruption, when the largest remnant mass is half that of the total mass, occurs at impact energies ~1.6-2.7 times the gravitational binding energy of the colliding bodies. Whereas [3] reports values ~2-3 times larger than this. We posit that a possible source for this discrepancy is due to the scale of the collision. [3] simulated collisions between bodies with total mass of ~10^{-6}-10^{-3} M_{Earth}; we simulate collisions between bodies with total masses of ~10^{-2}-10^{1} M_{Earth}. Interestingly, the transition between those size regimes coincides with the transition between subsonic to supersonic escape velocities for common geologic materials. This strongly suggests a scale dependency in giant impact phenomena and, indirectly, a ma-

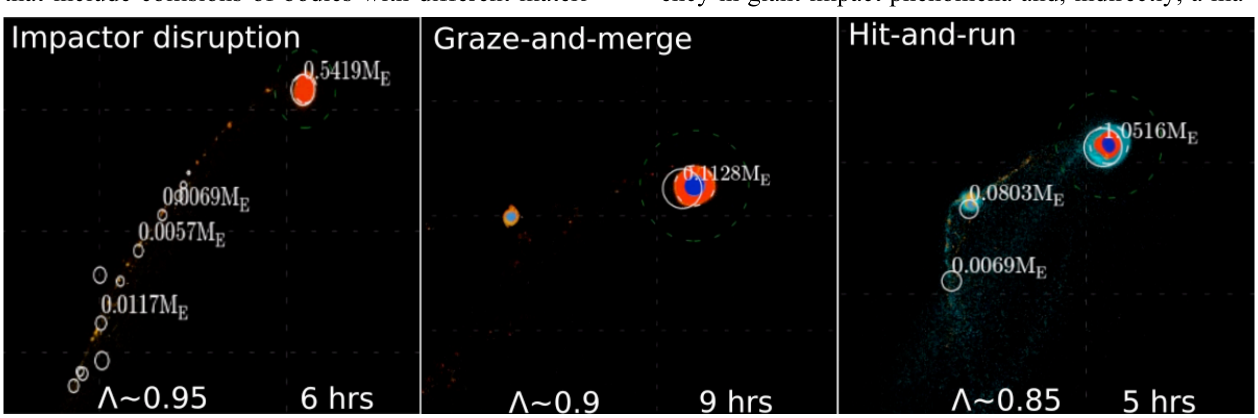

Figure 1: SPH visualizations of impacts between homogeneous (pure SiO_2) bodies (left), 2-layer (SiO_2-Fe) bodies (middle), and 3-layer (H_2O-SiO_2-Fe) bodies (right). All collisions have an impactor-to-target mass ratio of 0.2, impact velocity, $v_{imp} = 1.6v_{esc}$, and impact angle, $\theta_{imp} = 30°$. Target masses from left to right are 0.5, 0.1, and 1.0 M_{Earth}

terial dependency since the effect may be governed by the sound speed of the media.

We also examined the effect of density stratification on the outcomes in giant impacts. The high-resolution sampling of our database allowed us to uncover a fundamental difference in the behavior of hit-and-run collisions between bodies of different material compositions. More homogeneous bodies tend to undergo messier hit-and-run collisions, producing more mass in debris (See Figure 1). The 'runner' in a hit-and-run collisions under these circumstances is also more likely to be disrupted and gravitationally reaccumulated downrange. In contrast, more strongly density-stratified bodies show cleaner hit-and-run phenomena, and the transition to hit-and-run in the impact parameter space is sharper.

We develop a parameter Λ in [8] that provides a scalar representation of the degree of density stratification of the colliding bodies. Its value is equal to the ratio of the analytically-derived gravitational binding energy of the bodies (assuming they are uniform density) and the numerically-derived gravitational binding energy. Values of $\Lambda \approx 1$ indicate a homogeneous distribution, whereas our 3-layer, water-rich planets have values of $\Lambda \approx 0.85$. In Figure 2 we present our empirical fit to the hit-and-run angle as a function of Λ and the impactor-to-target mass ratio. We generally find that clean hit-and-run outcomes occur at higher angles in homogeneous bodies. This is an intuitive result as centrally-condensed bodies are less thoroughly disrupted in tidal interactions than those which do not possess cores, under identical conditions. Since growing planets undergo increased central compression and the densities of different materials produce different stratification structures, this result is an indirect violation of both material invariance and scale invariance.

Conclusion: We demonstrate new potential controls on the outcomes of giant impacts [8]. Collisions between bodies larger than ~10^{-2} M_{Earth} exceed the sound speed of geologic materials and tend to produce more erosive collisions as a consequence. This effect violates the commonly-assumed scale and material invariance of outcomes of giant impacts; however, we reserve more careful examination of scale invariance for future work. Considering this effect may be dependent on the bulk sound speed of the geologic material, special attention must be placed on the equation of state and initial thermal state of different studies in the giant impact literature.

We also demonstrate that the occurrence of hit-and-run outcomes is governed by the density stratification (differentiation state) of the colliding bodies [8]. Primitive, undifferentiated bodies tend to undergo more erosive hit-and-run collisions than their differentiated counterparts for the same impact conditions. We examine the potential reasons for this difference, and consider the possibility that it is due to tidal effects. However, given the results of material dependence, a complicated interplay between thermodynamics and stratification likely governs the hit-and-run transition.

In summary, we find fundamental differences between the accretionary behavior of primitive, less-stratified bodies, and evolved, differentiated bodies. Under these findings, stripped cores of planetary embryos will revert back to more erosive style hit-and-run outcomes. Furthermore, larger bodies overall may tend to undergo more erosive collisions across a range of impact parameters, potentially providing a natural bottleneck for the growth of bodies larger than roughly the Moon.

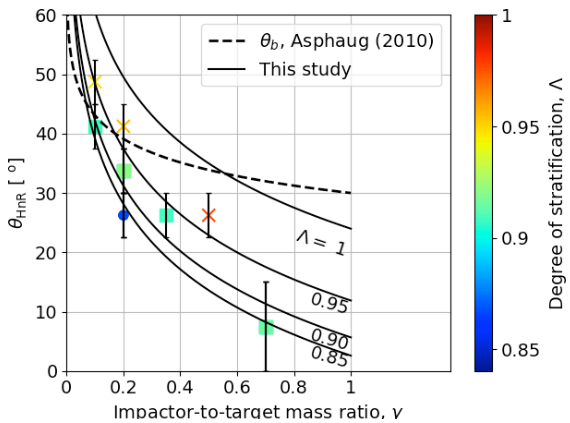

Figure 2 – Angles at which hit-and-run outcomes occur for different material types (density stratifications). The top of the error bars denote the minimum angle where hit and run occurs, the bottom of the error bars indicate the largest angle at which hit and run is not seen to occur. Symbols represent different material types: 'x' represents pure SiO_2 bodies, squares represent 'chondritic' SiO_2-Fe bodies, circles represent water-rich, H_2O-SiO_2-Fe bodies. The grazing angle from [5] is shown as a dashed line. The solid lines represent our empirical fit to the hit-and-run angle.

References: [1] Agnor & Asphaug (2004) *ApJ*, 613(2), L157-160, [2] Benz & Asphaug (1999) *Icarus*, 142(1), 5-30, [3] Movshovitz *et al.* (2016) *Icarus*, 275, 85-96, [4] Marcus *et al.* (2010) *ApJ,* 719:L45-L49, [5] Asphaug (2006), *Chemie de Erde*, 70, 199-219, [6] Chambers (2013), *Icarus,* 224, [7] Leinhardt & Stewart (2012) 751:32, [8] Gabriel, T.S.J. *et al*. (submitted, *ApJ*), [9] Foreman-Mackey *et al*. (2013) *Astronomical Soc. Of the Pacific*, [10] Shoemaker (1961).