EPSC Abstracts
Vol. 13, EPSC-DPS2019-298-4, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

On the Systematics of Giant Impacts

Travis S.J. Gabriel (1), Erik Asphaug (2), Alan P. Jackson (3), Alexandre Emsenhuber (2), Saverio Cambioni (2), Andreas Reufer (4), Martin Jutzi (4), and Willy Benz (4)
(1) School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, (2) Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, (3) University of Toronto, Toronto, Canada, (4) University of Bern, Bern, Switzerland (Travis.Gabriel@asu.edu)

Introduction

Collisions are a dominant process in late-stage planet formation where planetary embryos undergo mutual accretion and erosion to eventually produce the present-day terrestrial solar system. Whether the formation of planetary embryos occurs under the classical framework or under modern frameworks, *e.g.* 'pebble accretion', their mutual accretion to produce terrestrial planets is a necessary outcome. These energetic events occur at velocities roughly that of the mutual escape velocity of the two bodies. Thus, embryo-embryo collisions are relatively gentle compared to mutual collisions between minor bodies stirred by larger gravitational perturbers. We demonstrate that since collision velocities between major bodies go as $v_{\mathrm{imp}} \propto M^{1/3}$, impacts occur at sub-sound speed velocities at early epochs and supersonic velocities at later epochs.

We demonstrate that this introduces non-negligible effects on the erosive nature of giant impacts. We also demonstrate the density stratification plays a non-negligible role in the outcomes of giant impacts. Together, these results demonstrate a more nuanced approach is required in modeling the outcomes of giant impacts; the internal structure of the planets must be tracked in N-body simulations and consideration for the absolute velocity is important.

1. Analyzing impact outcomes

We utilize a database of over 1,000 Smoothed Particle Hydrodynamics (SPH) impact simulations that span materials (modeled with the M-ANEOS/ANEOS equation of state), impact velocities, and impact geometries relevant to late-stage planet formation [1]. Collisions span sub-sound speed to supersonic velocities allowing for us to identify scale-dependent effects, in addition to the effects of the internal structure. As giant impacts have yet to be observed (though some candidates exist, *e.g.*, [2]), we rely on hydrocode simulations as the 'ground truth' for understanding their outcomes. In this manner, giant impact studies are uniquely susceptible to numerical effects as compared to cratering collisions for which there are laboratory analogues and observable craters.

Hydrodynamical models of collisions are computationally intensive to simulate (several hours to days or weeks of compute time). To provide predictions for giant impact outcomes in N-body planet formation simulations, surrogate models or scaling laws can be developed which avoid running a full hydrocode simulation. This can be achieved via analytical, *e.g.* [3], or data-driven [4] approaches. These methods are complementary as the former provides analytical and physical insight, while the latter approach is assumption free. Herein, we report findings from the giant impact model of [3].

1.1. Density stratification

Hit and run (HnR) occurs when the geometry of the collision is sufficiently glancing and at sufficiently high velocity; the impactor continues downrange in a deflected trajectory. [5] provides an analytic relation that describes the impact angle at which the velocity vector no longer intersects the target,

$$\theta_{\mathrm{graz}} = \sin^{-1}\left(\frac{R_{\mathrm{tar}}}{R_{\mathrm{tar}} + R_{\mathrm{imp}}}\right), \quad (1)$$

however, this was meant as a geometric guideline and was not intended as a robust indicator of the occurrence of HnR across a range of impact conditions. Nevertheless, we find it accurately describes the occurrence of HnR for small values of the impactor-to-target mass ratio (γ), but underestimates the occurrence of HnR for more similar-sized bodies [3].

To understand the possible role of internal structure on HnR outcomes, we generalize the stratified structure of colliding bodies into a single parameter, Λ, a function of the actual potential energy of the bodies $U_{\mathrm{G,n}}$ and the constant-density approximation $U_{\mathrm{G,a}} = \sqrt{\frac{3GM^2}{5R}}$,

$$\Lambda = \frac{U_{\mathrm{G,a}}^{\mathrm{tar}} + U_{\mathrm{G,a}}^{\mathrm{imp}}}{U_{\mathrm{G,n}}^{\mathrm{tar}} + U_{\mathrm{G,n}}^{\mathrm{imp}}}, \quad (2)$$

where the superscripts represent target and impactor quantities and Λ has a dynamic range of $\sim$0.8-1.0; water-rich bodies represent the lower range and stripped cores or primitive (undifferentiated bodies) represent the upper limit. We find this parameter allows for a new prediction of HnR as a function of the density-stratification of colliding bodies [3]. The updated HnR model in [3] demonstrates that HnR occurs at lower angles in bodies with differentiated internal structures. Thus, stripped cores or primitive bodies will tend to undergo inefficient merging collisions. Differentiated and/or volatile-rich bodies on the other hand have a higher probability of undergoing a series of HnR events (explored by [6]), prolonging their accretion timescales.

1.2. Scale dependence

Impact velocities of growing planetary embryos are governed by their mutual escape velocity, $v_{\mathrm{esc}} \propto M^{1/3}$, with $\sim$95% of collisions occurring at $< 1.6 v_{\mathrm{esc}}$ [3, 7]. As bodies approach $\sim 10^{-3} M_{\oplus}$ their collision velocities reach one to several kilometers per second, exceeding the sound speed of geologic materials and introducing shocks. These shocks produce irreversible increases in entropy, potentially driving the thermal expansion and ejection of escaping material. In [3] we find a distinct increase between the disruption criterion of bodies less than $\sim 10^{-3} M_{\oplus}$ [8] and our simulations of larger masses. This indicates a breakdown of the common assumptions of scale-independence and material-independence in the outcomes of gravity-dominated giant impacts.

2. Conclusion

We find that giant impact outcomes depend not only on scale, but also on internal structure and composition. This is especially important since concentration of the mass distribution shifts the colliding cross section and angular momentum, the tendency being for more compacted planets to have effectively more grazing-types of collisions. This represents a shift in the analysis of giant impacts and their outcomes, by including gravitational self-compression and material stratification. Absent strong perturbations by migrating gas giants, collisions between the early-formed, undifferentiated embryos will be less likely to result in hit and run, reducing their accretionary timescales. As these bodies grew to sizes of 100-1000 km, radioactive heating would have led to melting and differentiation, and thus a strong density stratification (metallic iron and primitive silicate composition). The accretion timescale would then increase due to the relative prevalence of hit-and-run collisions as described by our findings. At this scale, large planetary embryos ($> 10^{-3} M_{\oplus}$) would undergo extensive shock processing of the interacting material in the collision, potentially producing a greater amount of vapor and debris. Effectively, this may separate terrestrial planet formation into two or more stages marked by the timing of differentiation and growth beyond $\sim 10^{-3} M_{\oplus}$. The interplay of these effects may produce natural bottlenecks in the formation of planetary systems.

Acknowledgements

This work was supported by the NASA Earth and Space Science Fellowship award PLANET18F-0036.

References

[1] Reufer, A.: Collisions in planetary systems. PhD thesis, 2011.

[2] Lisse, C.: Circumstellar dust created by terrestrial planet formation in HD 113776, ApJ, 673(2), 1106-1122, 2008.

[3] Gabriel, T.S.J., *et al.*: Gravity-dominated collisions I. Empirical model for largest remnant masses with treatment for 'hit and run' and density-stratification, ApJ, In review.

[4] Cambioni, S. *et al.*: Realistic On-The-Fly Outcomes of Planetary Collisions: Machine Learning Applied to Simulations of Giant Impacts. ApJ, 875(1), 40, 2019.

[5] Asphaug, E.: Similar-sized collisions and the diversity of planets. ChEG, 70, 199-219, 2010.

[6] Emsenhuber, A. and Asphaug, E.: Fate of the Runner in Hit-and-run Collisions. ApJ, 875(2), 95, 2019.

[7] Chambers, J.E.: Late-stage planetary accretion including hit-and-run collisions and fragmentation, Icarus, 224, 43-56, 2013.

[8] Movshovitz, N. *et al.*: Impact disruption of gravity-dominated bodies: New simulation data and scaling, Icarus, 275, 85-96, 2016.