THE ENERGY BUDGETS OF GIANT IMPACTS. Philip J. Carter[1], Simon J. Lock[2] and Sarah T. Stewart[1]. [1]Department of Earth and Planetary Sciences, University of California, Davis, CA 95616 (pjcarter@ucdavis.edu); [2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138.

Introduction: The final stages of terrestrial planet formation are likely dominated by a series of energetic impacts. Through these giant impacts, the final system of planets is assembled. In our own solar system, the final giant impact with the proto-Earth is believed to be responsible for the formation of the Moon.

Giant impacts can have a variety of different outcomes, from merging to hit-and-run, and even erosion. Leinhardt and Stewart [1] analysed the results of impact simulations to determine the energies required for catastrophic disruption (in which half the total mass is dispersed) throughout the gravity regime, and Stewart and Leinhardt [2] found that the giant impact stage has a diverse range of outcomes. Furthermore, disruption does not closely follow energy scaling as the kinetic energy of the impact is not all used to disperse material from the colliding bodies.

Here we examine the energy budgets of giant impacts in more detail, examining the changes in internal, kinetic and gravitational potential energy as the impacts proceed. We have simulated a wide range of giant impacts that produce approximately Earth mass final bodies, varying the mass ratio, impact angles, and impact velocities [3]. We include examples of proposed Moon-forming events: canonical [4], similar mass impactors [5], and small, fast impactor hitting a rapidly rotating proto-Earth [6].

Numerical Method: The impact simulations were all carried out using a modified version of the smoothed particle hydrodynamics (SPH) code GADGET-2 [3,6,7]. This code uses tabulated equations of state for iron and forsterite (MANEOS, [6,8]) to model the cores and silicate portions of strengthless planetary embryos.

The sizes of targets and impactors, target spins, impact velocities and impact parameters were chosen to sample both the range of impact scenarios proposed for the Moon-forming giant impact and the statistical distribution of impact parameters from *N*-body simulations of terrestrial planet formation [e.g., 9].

The energy terms are large and substantial amounts are exchanged between internal (IE), kinetic (KE), and gravitational potential (PE) energies during the event. We present the total giant impact energy budget defined by the initial KE, initial IE, and initial PE-min(PE). The offset factor min(PE) converts the PE term to a positive value. Note that min(PE) occurs during the early stages of the impact and is a more negative value than either the beginning or end states.

Results: A common feature across the range of possible moon-forming giant impacts is a significant increase in the total IE of the bodies (Figs. 1-3). A portion of PE and KE of the event is converted to IE rather than being used to raise material away from the gravitational center. This heating leads to substantial melting and vaporization.

The IE increases quickly as the two bodies collide and the shock compresses material near the impact site. Near the maximum compression stage, the distance between the centers of the colliding bodies decreases in a configuration that is gravitationally unstable. At this point, the PE reaches its minimum.

Much of the IE energy from the maximum compression stage is converted back into KE and PE as the bodies release and expand from the shock. During this decompression phase, some material moves away from the center of mass, increasing the contribution of potential energy to the energy budget, and decreasing the KE as it decelerates.

The PE reaches a maximum as the bodies reach maximum decompression, typically about one hour after the start of the impact, after which the displaced material begins to fall back into the potential well. This falling material heats the post-impact body via secondary shocks, causing a gradual increase in IE, and producing a hot vapor atmosphere during the period of gravitational re-equilibration.

IE accounts for a larger fraction of the energy budget in canonical Moon-forming impacts, in which a Mars-sized impactor has an oblique collision with an approximately Earth-sized target, than in the other impact scenarios (Fig. 1). Unsurprisingly the contribution of kinetic energy is lower in low velocity impacts, and with a small impactor (mass ratio ~0.1) the gravitational potential energy change is modest.

The similar mass impactor scenario from Canup [5], has a larger relative contribution from PE throughout, but still exhibits a significant increase in IE (Fig. 2). Much of the KE is converted in the impact; however, the secondary impact in the graze-and-merge event converts some of the PE back into KE resulting in a fast-spinning post-impact body. The inflated post-impact body maintains a significant contribution from PE. The shock from the second contact in the graze-and-merge generates substantial ejecta that holds a significant amount of KE.

The small, fast impactor hitting a rapidly spinning Earth-sized target has a much larger contribution to the energy budget from KE (Fig. 3). Since these collisions result in a fast-spinning body and substantial ejecta, the kinetic energy remains high after the collision.

In all the possible Moon-forming impacts, the energy budget has a significant contribution from PE at late times due to material raised above the original surface of the target, placed into orbit around the remnant or ejected. This is in contrast to the situation for small, cratering impacts in which the PE is insignificant [10]. It is important to note that the energy budget immediately after the impact does not represent the final state of the body. The PE and KE change as the planet cools [11].

In most of these simulations, there is a slight increase in the total energy of the simulated material, generally on the order of a few percent. There is often a bump in energy that coincides with the potential minimum, followed by a more gradual rise. We suggest that this small energy error in the simulation is due to imperfect treatment of the shock energy using the tabulated equation of state, and it will be investigated in more detail. We note that this error in total energy is substantially smaller than the increase in internal energy.

Conclusions: Giant impacts lead to significant increases in the internal energies of the bodies, due to the release of kinetic and potential energy. The final energy budgets have a significant contribution from gravitational potential energy, which could be neglected in impact cratering events [10]. The different models for the Moon-forming impact have very different energy budgets. The distribution of energy after a giant impact is important for understanding the amount of melting and vaporization, and the thermal state of the final planet. SPH simulations of giant impacts may exhibit energy errors due to imperfect treatment of the shock energy.

References: [1] Leinhardt Z. M. and Stewart S. T. (2012) *ApJ, 745*, 79. [2] Stewart S. T. and Leinhardt Z. M. (2012) *ApJ, 751*, 32. [3] Lock S. J. and Stewart S. T. (2017) *JGR Planets, 122*, 950. [4] Canup R. M. and Asphaug E. (2001) *Nature*, *412*, 708. [5] Canup R. M. (2012) *Science, 338*, 1052. [6] Ćuk M. and Stewart S. T. (2012) *Science, 338*, 1047. [7] Marcus R. A., Stewart S. T., Sasselov D., Hernquist L. (2009) *ApJ, 700*, L118. [8] Melosh H. J. (2007) *MAPS, 42*, 2079. [9] Quintana E. V., et al. (2016) *ApJ., 821*, 126. [10] O'Keefe J. D. and Ahrens T. J. (1982) *JGR, 87*, 6668. [11] Lock S. J., Stewart S. T., Ćuk M. (2018) *LPSC 49*.

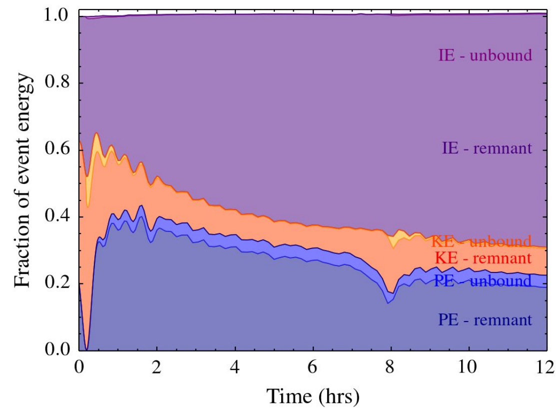

Figure 1: Evolving energy budget of a canonical Moon-forming giant impact. In this simulation a 0.13 $M_⊕$ body collided with 0.9 $M_⊕$ body with an impact parameter of 0.74, at a velocity of 9 km s^{-1}. The feature at 8 hrs is the accretion of a surviving portion of the impactor. min(PE) = -2.55e32 J.

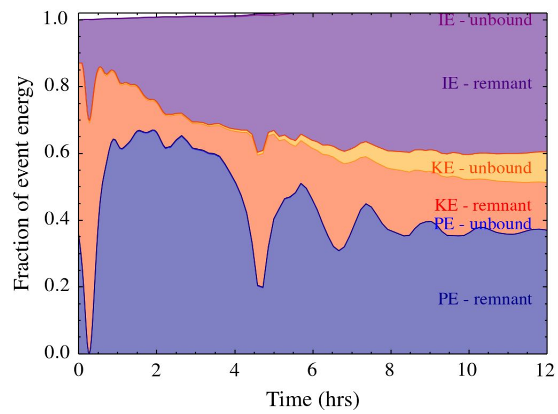

Figure 2: Evolving energy budget of a similar mass impactor graze-and-merge impact. In this simulation a 0.47 $M_⊕$ body collided with 0.57 $M_⊕$ body with an impact parameter of 0.55, at a velocity of 10 km s^{-1}. The feature at 4.5 hrs is the secondary impact. min(PE) = -2.59e32 J.

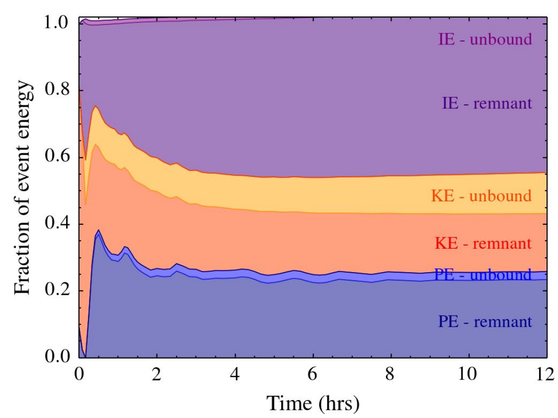

Figure 3: Evolving energy budget of a high angular momentum impact. In this simulation a 0.05 $M_⊕$ body collided with a spinning 1.05 $M_⊕$ body (spin period 2.4 hrs) with a retrograde impact parameter of 0.3, at a velocity of 20 km s^{-1}. min(PE) = -2.80e32 J.