HIGH COLLISION VELOCITIES BETWEEN PLANETESIMALS DURING PLANET GROWTH AND MIGRATION. Philip J. Carter[1], Erik J. Davies[1], Simon J. Lock[2] and Sarah T. Stewart[1]. [1]Department of Earth and Planetary Sciences, University of California, Davis, CA (pjcarter@ucdavis.edu); [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA.

Introduction: Based on the formation ages of meteorites and Mars, the protoplanetary disk was home to large numbers of planetesimals during the growth of planets. During this period, planetesimals would have been found throughout the disk. It is commonly assumed that planetesimals retain low relative velocities during the lifetime of the solar nebula, stirred only moderately by nearby embryos, and damped by the nebular gas. While this is largely true in a disk unperturbed by giant planets, it is not the case in the presence of growing and migrating gas giants [1].

While low velocity impacts in the gravity-dominated regime result in efficient accretion, higher impact velocities lead to a variety of different outcomes, from hit-and-run and erosion to super-catastrophic disruption [2]. We have carried out numerical simulations of planet formation that include planetesimal-planetesimal impacts in order to quantify the probability of such collisions. Using experimentally derived equations of state of planetesimal materials [3], we have determined velocity thresholds for impact-induced vaporization. Here, we use these thresholds to examine the mass of material processed by vaporizing impacts during planetary accretion.

Numerical Method: *N*-body simulations of terrestrial planet growth were carried out using a modified version of the parallelized code PKDGRAV [4]. These simulations track many thousands of bodies and calculate the gravitational acceleration for every body in the simulation, including the planetesimals. These simulations included a state-of-the-art collision model to predict the outcomes of collisions at all velocities and impact angles [2, 5]. Debris smaller than a specified resolution limit is placed in annular bins in the corresponding location throughout the disk. The debris is reaccreted by planetesimals and embryos as they pass through the annuli. In this manner, a portion of the mass in resolved bodies is processed through small-scale ejecta.

We carried out two types of simulations: a set covering only the terrestrial planet region with no perturbation from giant planets, and a set based on the Grand Tack model [6] in which Jupiter migrates inward and then outward through the inner disk. Simulations began with a range of planetesimal sizes with the majority having radii of ~200 km. These planetesimals experienced aerodynamic drag from the nebular gas. After ~2 Myr (the time corresponding to giant planet migration), the nebula dispersed with an e-folding timescale of 0.1 Myr. Further details of these simulations can be found in Carter et al. [7].

We extracted the impact velocity of every collision that occurred during the accretion simulations and the mass of small debris that each collision produced. These impacts were then compared to velocity thresholds at which shock pressures sufficient for vaporization upon release are achieved, as determined via shock experiments (see [3]).

Results: In all the simulations, we see a wide range of impact velocities, with small numbers of both perfect merging collisions and super-catastrophic disruptions. With the exception of perfect merging, or perfect bouncing collisions, all impacts can produce small debris. Over the 20 Myr simulations, we find that the cumulative mass ejected as small debris can exceed the total simulation mass. Since the majority of this debris is reaccreted by the resolved bodies and more debris is produced by subsequent collisions, the total mass of small debris produced over the duration of the simulation can exceed the total available mass in the disk. However, this does not necessarily mean that all of the mass is processed through debris because it is not possible to determine what fraction of the mass is processed only once versus many times.

We show the distribution of impact velocities in a giant planet migration simulation in Fig. 1. Before migration begins, the inner solar system collision velocities are mostly low except where planetesimals are excited via resonances with Jupiter. We note that the majority of all impacts occur during this initial 2 Myr period when there are many small bodies; as accretion proceeds the number of planetesimals drops and the time between collisions becomes longer. During the inward and outward migration, there is a large spike in impact velocities, with a substantial fraction of impacts having velocities above 10 km s^{-1}. As the migration ends and accretion continues, low velocity impacts begin to dominate again, but a significant number of high velocity planetesimal impacts continue to occur in the inner disk long after the outward migration.

High impact velocities lead to vaporization of the impacting materials, which can change the collision outcome [8, 9], initiate new planetesimal formation [10, 11], and lead to changes in bulk chemistry [9]. The critical impact velocity corresponds to the shock pressure needed for the onset of vaporization upon decompression to the ambient pressure of the nebula, or to the material triple point after dispersal of the nebula. The critical impact velocity for ice is ~1 km s^{-1} [3]. Based on the impact velocities seen in our simulations and the planetesimal eccentricities found by Raymond & Izidoro [1], we expect vaporizing collisions to be common amongst icy planetesimals near growing or migrating giant planets.

For the refractory silicate forsterite, in warm, recently differentiated planetesimals, we have determined the critical velocity for the onset of vaporization to be ~6 km s^{-1} [3]. Fig. 1 demonstrates that there are many collisions during and after the migration of Jupiter that exceed this threshold, and hence we expect many collisions that induce partial vaporization of rocky planetesimals. In Fig. 2, we show the total mass of small debris ejected in impacts both above and below this threshold velocity. There is a substantial mass of material processed through vaporizing impacts (up to 50%).

As discussed by Stewart et al. [8] and Davies et al. [9], the results of vaporizing collisions differ substantially depending on whether they occur in the nebula or after the nebular gas has dissipated. As Fig. 1 shows, high velocity impacts occur both during and after the nebula phase of the protoplanetary disk. Giant planet growth necessarily takes place in the nebula, and the planetesimal impacts induced by this process may lead to the production of new planetesimals with properties similar to chondrites [10, 11]. After the dispersal of the nebula, vapor plumes produced by high velocity impacts evolve differently, and may lead to separation of dust and larger droplets which would alter the moderately volatile element composition of terrestrial planets (see Davies et al. [9]).

Conclusions: Giant planet growth and migration leads to a large number of high velocity planetesimal-planetesimal impacts. These disruptive impacts can exceed the pressures required for vaporization of ice and silicates upon decompression, leading to very different outcomes compared to low velocity impacts. During inward and outward migration of Jupiter up to 50% of the mass of rocky material in the inner solar system can be processed through vaporizing impacts. Collisional processing has implications for the formation of new planetesimals and the compositions of growing terrestrial planets.

Acknowledgements: This work is supported by DOE-NNSA grant DE-NA0002937; NASA grant NNX15AH54G; NASA grant NNX16AP35H (EJD); and UC Office of the President grant LFR-17-449059.

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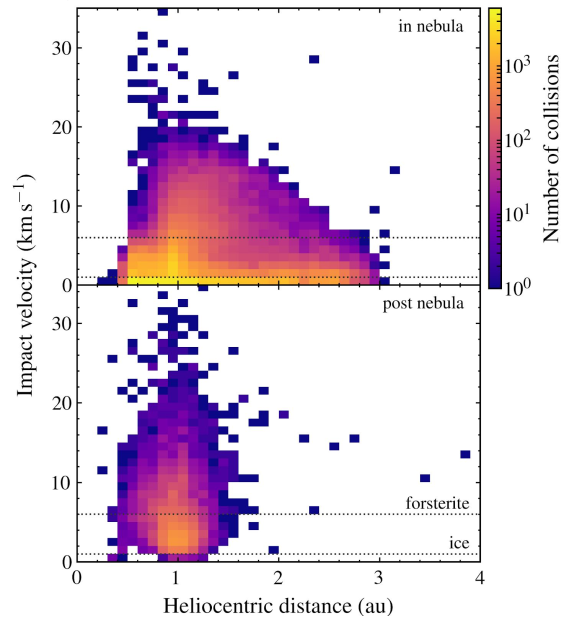

Figure 1: Impact velocity distribution as a function of heliocentric distance in a giant planet migration simulation. Dotted lines show critical velocities. There are many impacts in both phases that exceed the threshold for vaporisation of silicates (upper dotted line).

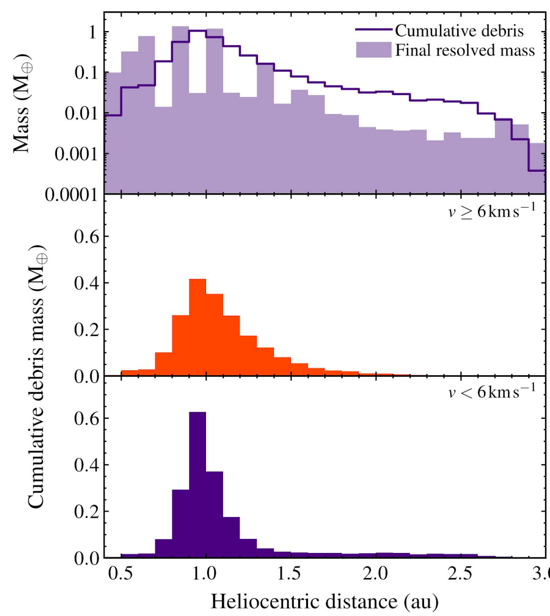

Figure 2: Mass of unresolved debris ejected in a giant planet migration simulation. A substantial fraction of this debris is produced in collisions that exceed the threshold for vaporization of silicates.