CHEMICAL AND HF/W ISOTOPIC CONSEQUENCES OF LOSSY ACCRETION. C. A. Dwyer, F. Nimmo, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz, CA 95064 (cadwyer@ucsc.edu)*, J. E. Chambers, *Dept. Terrestrial Magnetism, Carnegie Instit. Wash., Washington, DC 20015.*

Introduction. The late stages of planetary accretion involve stochastic, large collisions [1]. Although such collisions are usually assumed to result in perfect mergers, many of the collisions may instead result in hit-and-run events [2] or erosion of existing bodies' mantles [3]. Impact-related erosion and fragmentation can have profound consequences for the rate and style of accretion [4, 5] and the bulk chemistries of terrestrial planets [6]. Here we present a preliminary investigation into the effects of late-stage accretion with multiple collision types and the consequences for bulk chemistry and isotopic characteristics of the resulting planets.

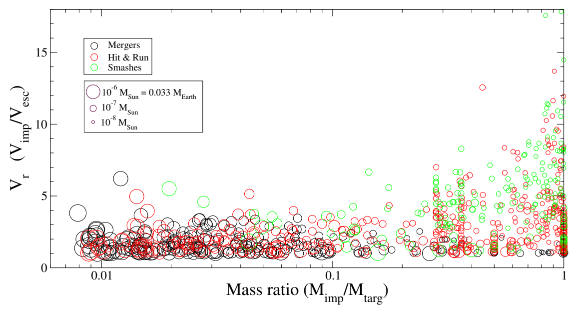

Figure 1: All collisions from the run, colour-coded based on collision type (black=merger; red=hit & run; and green=smash) with symbol radius $\propto$ (total mass)$^{1/3}$.

Model. Our model is composed of two parts: (1) the N-body accretion code tracks the orbital and collisional evolution of the terrestrial bodies and incorporates multiple collisional outcomes and (2) the geochemical post-processing evolves the chemistry in light of radioactive decay and impact-related mixing and partial equilibration.

N-body Model: 16 runs were performed by [7] using the MERCURY N-body code [8]; each run contained 153 initial bodies totaling 7.65×10^{-6} $M_\odot$ as well as Jupiter and Saturn in their current orbits with their current masses. In the run we present here, all planetesimals had the same initial mass, 5×10^{-8} $M_\odot$. Six different collisional outcomes are possible depending on the velocity (v_i), angle, mass ratio ($M_r = M_{imp}/M_{targ}$), and total mass of the impact (modified from [9, 10]). We have grouped them into three categories for our discussion here: (a) *perfect merger:* the target and impactor combine to form one body; (b) *hit & run:* the target and impactor survive unchanged; and (c) *smash:* the target and impactor interact in the collision, resulting in two or more bodies post-collision with mass and chemistry having been affected.

Bulk Chemistry: We model all bodies as being composed of two idealized reservoirs, a metallic 'core' and a silicate 'mantle', and we track the masses of these reservoirs for each body through the length of the simulation. All bodies are initially assigned a mantle mass fraction, *y*, of 0.7. In a smash, we build the largest post-collision body (LPCB) from (in order): the target core, impactor core, target mantle, and impactor mantle. The smaller post-collision body(ies) (SPCBs) are built from the remainder of the material (in the case of multiple SPCBs, they all are given the same bulk and isotopic chemistry).

Isotopic Chemistry: We track the Hf and W evolution of these bodies. Initial Hf and W isotopic ratios are set to CHUR. Bodies differentiate when they experience a perfect merger or a smash or at 3×10^6 yr, whichever occurs first. Radioactive decay occurs between impacts. We calculate the effect of an impact by assuming an idealized model of mixing and partial equilibration [11]. j is the mantle mixing fraction [12]. k is the core equilibration factor. Both k and j are free parameters; here we use $k = 0.3$ and $j = 1$. In the case of a smash, the impactor and target are divided into portions which go into the LPCB and the SPCBs. Then the isotopic composition of the LPCB is calculated as if it were a merger, but using the modified target and modified impactor portions.

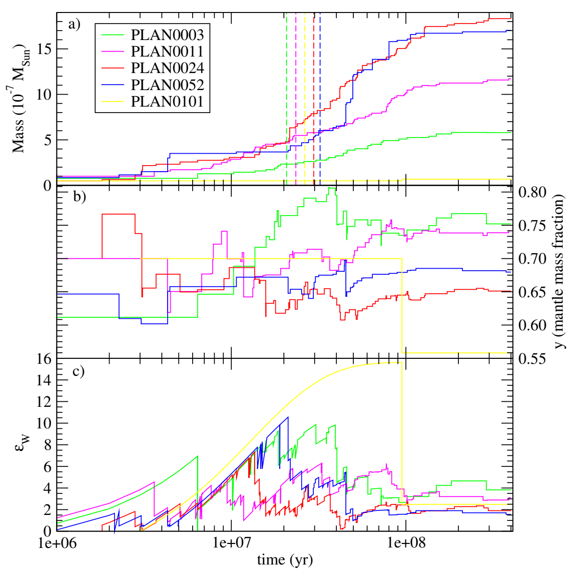

Figure 2: The temporal evolution of the surviving bodies. The colour used for each body is given in the key in part (a). In part (a), the single-stage core formation age (t_c) for each body is plotted as a vertical, dashed line and colour-coded to the body. Part (c) reports the tungsten isotopic anomaly relative to CHUR (ϵ_W) for the mantles of the bodies.

Results.

N-body Results: In order to have more meaningful statistics, for this paragraph only, we discuss the results of all 16 simulation runs. In each run, approximately half of the collisions are hit & runs, which is consistent with previous work [9, 13]. The timescale to accrete half the final mass is slightly faster than in otherwise identical simulations which used only perfect mergers [14]; however, the timescale to accrete the entirety of the final mass is longer. This is in contrast with

[5], who found that using two collisional outcomes (hit & runs and perfect mergers) "barely affected" the growth timescale relative to only perfect mergers.

Fig 1 shows all collisions in one run as a function of mass ratio (M_r) and velocity ratio ($v_r = v_i/v_{esc}$; where v_{esc} is the two-body mutual escape velocity). Mergers occur primarily at low M_r, low v_r, and have a total mass in the medium to large range. Smashes occur at high v_r and are more common with $M_r \approx 1$ and at low masses. These results suggest that damping of large bodies by dynamical friction is persistent through most of the accretion process.

Bulk Chemistry: Fig 2 tracks three parameters (mass, *y*, and mantle tungsten isotopic anomaly relative to CHUR (ϵ_{W})) as a function of time for each surviving body. Part (a) shows that overall, the mass increases, although there are occasions where small amounts of mass loss do occur. There is no one collision which delivers the majority of the mass for any body. Part (b) shows that an impact can increase or decrease *y*, depending upon the collision type as well as the masses and *y*'s of the target and impactor. (Note that PLAN0101 experiences only five collisions and four of them are hit & run events, so the evolution of this body may not be well resolved by this simulation.) Part (c) will be discussed with the isotopic results.

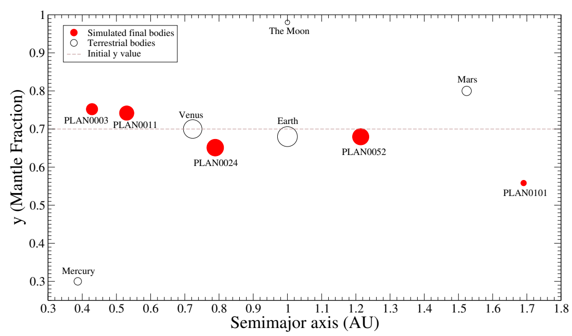

Figure 3: Comparing the bodies which survived the simulation to terrestrial bodies. Solid red symbols are from the simulation and hollow symbols are terrestrial data. Symbol radius $\propto$ (mass)$^{1/3}$. The mass–radius key is given in Fig 1.

Fig 3 plots final *y* against semimajor axis for the surviving bodies of the simulation as well as the terrestrial planets. The initial *y* value of the simulation is marked with a horizontal dashed line; our simulated planets lie both above and below this line. Our simulation reproduces the mass range of the terrestrial bodies well. The *y* of Venus, Earth, and Mars are reasonably well represented by our simulation but the Moon and Mercury are not.

Isotopic Chemistry: Fig 4 plots final ϵ_{W} against *y* for the surviving bodies of the simulation as well as the terrestrial bodies for which we have data. The ϵ_{W} results more than span the range of the terrestrial bodies; using a larger *k* (i.e., more core equilibration) would make the range more similar. Due to assuming constant values for *k*, *j*, and partition coefficients, all our simulated bodies have an Earth-like $f^{Hf/W}$ of 12.9.

The temporal evolution of ϵ_{W} of our simulated bodies is shown in Fig 2 (c). Collisions can increase or decrease ϵ_{W}. The single-stage core formation age (t_c) for each body is shown on Fig 2 (a). There is no obvious relationship between t_c and the mass history of the bodies.

Discussion. Lossy accretion affects both the physical and chemical results of terrestrial planet formation simulations. The time to complete accretion is longer in the multi-outcome case than in a perfect mergers case.

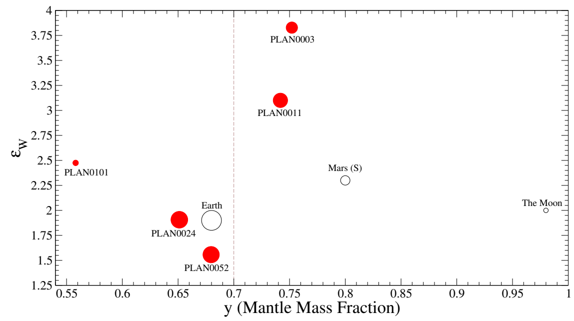

Figure 4: As per Fig 3. ϵ_{W} as defined in Fig 2.

The final *y* value of bodies can be either larger or smaller than the starting *y*, indicating that repeated collisional mass transfer affects bulk chemistry. Thus, the bulk chemistry of the terrestrial planets is unlikely to be identical to the composition of the material from which they accreted.

An individual collision can increase or decrease the *y* and the ϵ_{W} of a body, depending upon the collision style as well as the chemical composition and relative masses of the target and impactor.

There is no single impact event which defines the final state of the body, therefore talking about a single, specific age of formation does not make sense. Instead, it must be recognized that terrestrial planet formation occurs over a range of time spanning many tens to perhaps hundreds of millions of years.

Future Work. There is substantial work which remains on this project: Incorporating the method of [15] for determining bulk chemistry of a collision. Varing *k* [16] and *j* [12], calculate $f^{Hf/W}$. Incorporating the Pd/Ag system [17]. Analysing all 16 runs and comparing amongst the runs to examine stochastic versus systematic effects.

References

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