LOW-VELOCITY COLLISION, INEFFICIENT ACCRETION, HIT AND RUN DISRUPTION, AND THE STRIPPING OF PROTOPLANETARY CORES.
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Introduction: Small and middle-sized bodies in the solar system, and among major satellite systems, exhibit considerable variation in bulk composition, ranging from nearly pure iron, to rocky, to pure water ice, with all variation inbetween. Reconciling this diversity within the context of standard planet formation scenarios has led to the acceptance that a stochastic aspect must dominate, a so-called 'late stage' when most of the colliding matter is in similar sized bodies and most of the collisions are energetic, stirred up to the prevailing escape velocities of the largest objects [e.g. 1]. These are similar-sized collisions (SSCs), occurring between planetary bodies of comparable size, although generally unequal mass, at velocities ~1 to a few times their mutual escape velocity [2]. At the largest planetary scales we call them giant impacts.

Contrary to the prevailing assumption, accretion by SSC is inefficient [e.g. 3] owing to the conversion of gravitational binding energy and angular momentum [4]. When the colliding bodies are differentiated, this leads to selective loss of the lower density outer materials, accounting for diverse final compositions [2].

Planetary Impacts. Apart from a few general studies [e.g. 2, 3, 5] the loss of mantle material during SSCs has mostly been studied in detail in a few specific contexts. The best studied so far is the proposed collision between a Mars-sized protoplanet and the proto-Earth, producing the iron-poor Moon [e.g. 6, 7]. Mercury's giant iron core can also be explained by collisional removal of its mantle, either by impact shock [8], or alternatively [2] by hit and run stripping, in which a Mars-sized protoplanet loses much of its mantle when it collides into, but does not accrete with, a Venus-sized protoplanet. For the outer solar system, it has recently been proposed [4] that the accretion of Titan by a sequence of giant impacts spawned the ice-rich middle-sized moons of Saturn, analogous to the Moon's formation from the mantles of two merging terrestrial planets [7].

Planetesimal Impacts. At planetesimal scales, the accretion inefficiency of SSCs has also been used to explain how early populations of partly molten planetesimals may have formed chondrules [9, 10] common to meteorites. Also, hit and run collisions in the early terrestrial zone have been proposed to explain the stripping of mantle silicates from the iron cores of Vesta-like planetesimals with Fe-Ni cores [e.g. 11, 2]. A feature of SSCs at planetesimal scales is that they are low velocity, generally much slower than 1 km/s, typically the speed of a car crash. Instead of blasting off target mantle material by shock, it strips off the mantle of the less massive of a collising pair by mechanical shears, rotational torques, and tides [2].

This scenario runs contrary to the canonical model, in which differentiated planetesimals were gradually battered to bits by high-velocity impacts over billions of years [12], an idea that is increasingly incompatible with asteroid and meteorite evidence. In particular, asteroid families formed by the disruption of Vesta-like bodies are absent [see 13], while Vesta's crust is well preserved, making it a miraculously sheltered planetesimal that kept its head when all about were losing theirs [14]. Nonetheless it is true that iron is stronger than rock [12], and this may yet play a role in the fact that more than half of the known parent bodies of meteorites appear to be iron-rich cores [15].

Evidence in Meteorites. Iron-rich meteorites preserve convincing evidence that mantle stripping occurred under low velocity conditions. Diverse cooling rates in three groups of iron meteorites suggest they were derived from metallic bodies 50-150 km in radius which cooled with as little as a few kilometers of overlying silicate mantle (~2-30 vol.% silicate) [11, 16]. This implies a high efficiency of mantle stripping, a conondrum that may be explained by multiple hit and run events. This may seem like special pleading, until it is understood that hit and run is as common as accretion, in nominally-excited planetesimal swarms [2].

Pallasites and mesosiderites are stony-iron breccias formed by impact mixing of molten core metal with mantle or crustal material, without shock [e.g. 16]. Hypervelocity impacts between asteroids do not mix target and projectile materials efficiently, but they cause extensive shock damage that is not observed in these meteorites. Low velocity stripping and mixing may be useful in explaining these and other meteorites, and we shall report on studies that are underway.

Methods: In previous work [17] we performed ~1300 simulations of SSCs involving various kinds of bodies, using the SPH code SPHLATCH, incorporating self-gravity and using ANEOS to model SiO_2, iron, and water [18]. We have now analyzed these runs for mantle loss, considering two kinds of completely differentiated bodies: (Fig. 1) a bulk chondritic set with a 70wt% silicate mantle and a 30wt% iron core, and (Fig. 2) an ice-rich set with 50wt% water ice, 35wt%

silicates and 15wt% iron. These bodies, modeled at various sizes, are simulated using ~10,000-70,000 SPH particles, enough to resolve the largest and any possible second-largest remnants. For each set we vary four fundamental collision parameters: target mass (M_{tar}), impactor mass relative to target mass ($\gamma = M_{imp}/M_{tar} < 1$), impact angle ($\theta_{imp}$), and impact velocity relative to the mutual escape velocity of both the target and the impactor (v_{imp}/v_{esc}). The remnants are determined at $50\tau_{coll}$ after the collision, where $\tau_{col} = 2\ (R_{imp}+R_{tar})\ /\ v_{imp}$. This corresponds to 30-50h for $v_{imp}=v_{esc}$.

Results: After a collision, the largest remnant is mainly made up of the previous target body, while a possible second remnant originates mainly from the impactor. For the largest and possible second largest body, we compute the stripping efficiency, which is the change in mass for a particular component material, relative to the material's mass in the progenitor body. Stripping of the mantle from a differentiated target body requires intense shocks [5, 8]; here we focus on hit and run collisions and the second remnant (that is to say, the unaccreted impactor).

The silicate stripping efficiency of the second remnant is $\delta_{SiO2} = (M_{imp} - M_{sr})/M_{imp}|_{SiO2}$. So $\delta_{SiO2} = 0$ means that second remnant has kept all the silicate mass from the impactor, while $\delta_{SiO2} = 0$ means that it has been completely striped of silicates, according with the wide ranging cooling rates of iron meteorites.

Conclusions: SSC in general provide a suitable mechanism to explain compositional variety among planets, dwarf planets, and satellites, but only if the inefficiencies of accretion are taken into account. A series of hit and run collisions may be required to explain the existence of naked iron cores; while this is statistically plausible [2] much further work is remaining to reconcile dynamical models and meteoritics.

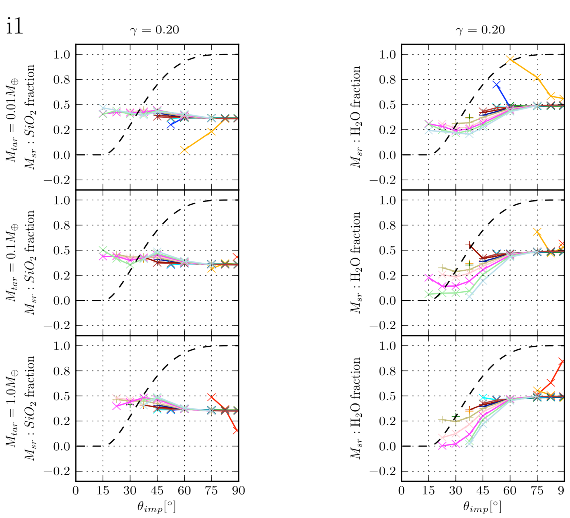

Fig 1. Silicate fraction for the second most massive remnant of a similar-sized collision, as a function of impact angle, for impact velocity colored as Fig. 2. For reference the black dashed line gives the relative impactor volume that would 'miss' the target assuming a straight trajectory after the time of impact.

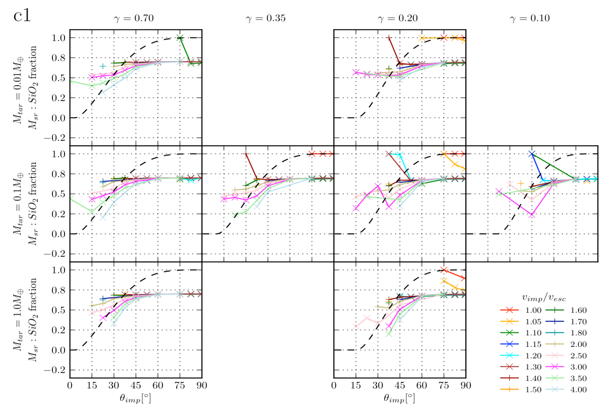

Fig 2. Mantle stripping is also important during similar-sized collisions when icy planetesimals accrete. Although meteorite evidence is not as readily available, highly variable bulk densities among icy satellites and KBOs suggest this has occurred [4]. Columns 1 & 3 are as above. Columns 2 and 4 show the corresponding water ice fraction for the icy bodies.

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