

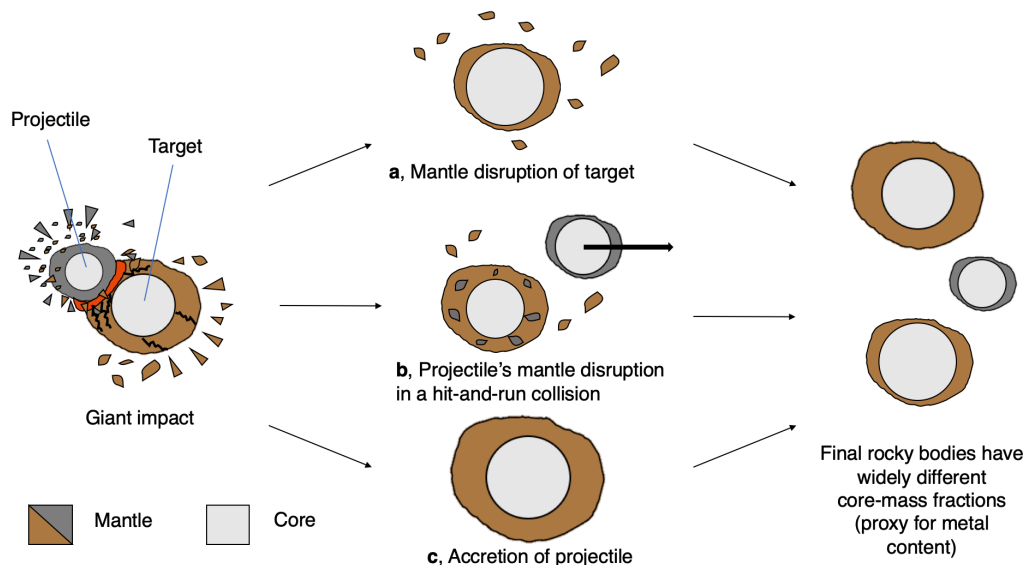
**HOW DO METAL-RICH BODIES FORM, FROM ASTEROIDS TO SUPER-EARTHS?** S. Cambioni<sup>1</sup>, E. Asphaug<sup>2</sup>, E. Y. Jung<sup>1</sup>, A. Emsenhuber<sup>3</sup>, B. P. Weiss<sup>1</sup>. <sup>1</sup>Massachusetts Institute of Technology, Cambridge MA, USA ([cambioni@mit.edu](mailto:cambioni@mit.edu)). <sup>2</sup>Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA. <sup>3</sup>Universitäts-Sternwarte, Ludwig-Maximilians-Universität München, München, Germany.

**Introduction:** Astronomical observations have revealed that metal-rich bodies exist both in the solar system and in exoplanetary systems [e.g., 1, 2, 3, 4]. The best-understood of such bodies is planet Mercury, whose uncompressed density is higher than Earth's due to its large metallic core accounting for ~70% of the planet's mass [1]. Some solar-system asteroids of Bus-DeMeo taxonomic class X are thought to be metal-rich due to their high radar albedo and bulk densities, and spectroscopic similarity to iron meteorites [2]. For example, (16) Psyche has a bulk density likely between 3,400 and 4,100 kg/m<sup>3</sup>, which may correspond to ~30 to ~60 vol.% metal [3]. At least 6 exoplanets are now classified as super-Mercuries because of their estimated iron-contents being larger than what expected from host-star chemistry [4]. The mass of the metallic core of a differentiated body compared to its mass (that is, its core-mass fraction) is a proxy for its bulk metal content [5]. Erosion of mantle materials by giant impacts may enhance the core-mass fraction of colliding bodies [6, 7, 8]. However, the large metal enrichment of some rocky exoplanets suggests that the colliding bodies may have had an already metal-rich composition before the collision [e.g., 9, 4]. To explore the interplay of early accretion processes and mantle erosion by giant impacts in forming metal-rich bodies, we designed a machine-learning model of giant impacts in which the core-mass

fraction of the colliding bodies varies between 0% and 100%. Here we present the rationale for this project (Figure 1) and outline our current results.

**Early versus late accretion.** The ubiquity of metal-rich bodies of all masses suggests that they may be a natural outcome of planetary formation. In the innermost part of a planetary system, aggregates of iron-rich condensates may overcome the mm-scale bouncing barrier more easily than silicate aggregates due to magnetic dipole-dipole interaction within the star magnetic field [10]. Growth of metal-rich building blocks may preferentially occur in correspondence of "rock lines" where refractory materials start to condensate [11]. Silicate condensates may experience faster orbital decay than metal condensates due to gas drag because of their lower bulk densities [e.g., 12]. The early stellar wind may drive an outward migration of refractory condensates seeding colder regions in the disk [13], but at the same time, silicate condensates may also be pushed toward colder regions of the disk by non-isotropic thermal radiation forces due to their lower thermal conductivity [e.g., 14]. The interaction between these processes, as well as their applicability across different planetary systems, is yet to be studied.

Rocky bodies are predicted to conclude their growth through giant impacts between similar-sized bodies [e.g., 8, 9]. Giant impacts may also form metal-rich



**Figure 1.** Two differentiated bodies collide in a giant impact. **a**, a head-on collision at high impact velocity results in target erosion. **b**, a hit-and-run collision at similar impact velocities results in two remnants. **c**, Accretion of the projectile do not typically lead to a significant increase of the target's core mass fraction. Does a combination of hit-and-runs, accretion and erosion explain the diversity of metal contents observed among rocky bodies, from asteroids like (16) Psyche to super-Earths?

bodies by eroding mantle materials from rocky bodies with a starting composition as expected from stellar chemistry [e.g., CI-chondritic for the solar system, 6, 7]. [8] studied the formation and differentiation of the solar-system terrestrial planets through giant impacts and found that the final range of core-mass fractions of rocky bodies that started with solar composition is similar to that of the solar system planets [8]. By contrast, [9] studied the in-situ formation of exoplanets and found that collisions at most double the core-mass fractions of super-Earths of initial solar composition, which does not explain some of the densest planets. A possible explanation (to be tested with formation models) is that metal-rich bodies tend to be found around stars with Fe-content higher than solar [4].

**Machine learning of giant impacts.** Previous works of giant impacts [e.g., 8, 15] used smoothed particle hydrodynamics (SPH) to study how the outcome of collisions vary as a function of colliding masses and the impact's velocity and angle. Most studies, however, assumed that the core-mass fraction of the colliding bodies was always equal to that of Earth, that is,  $\sim 30\%$  [5]. To study how metal-rich bodies form, we also need to explore the effect of the two core-mass fractions of the colliding bodies, which are proxies for their starting metal contents; Figure 1. A key challenge with this approach is that each SPH simulation has a runtime of hours to days, such that an exploration of the 6-dimensional parameter space would require millions of computer days. Therefore our approach is to replace the SPH code with a machine-learning representation of it [e.g., 8]. We train the machine-learning model on a new dataset of 1250 SPH simulations of giant impacts between differentiated bodies encompassing a wide range of masses, from asteroids to super-Earths, and including the effect of material strength. Our machine-learning model predicts the masses and core-mass fractions of the largest two collision remnants at a much faster runtime than the SPH code ( $\sim$  seconds versus days). The residuals between the model predictions and the SPH results are comparable to the numerical noise of the SPH code, and their correlation index is  $> 95\%$ .

**Mercury-like super-Earths.** In Figure 2 we show that there exists a family of giant-impact conditions (velocities and angles) in which the second-remnant of a hit-and-run collision between two super-Earths has a core-mass fractions larger or equal than Mercury (white and red areas). We focus on the composition of the second remnant because the fate of the target in a giant impact between super-Earths has been already studied by [15]. To reduce the dimensionality of the problem, we limit our study in Figure 2 to the case of two colliding super-Earths that have an Earth-like initial core-mass fraction. Formation of Mercury-like

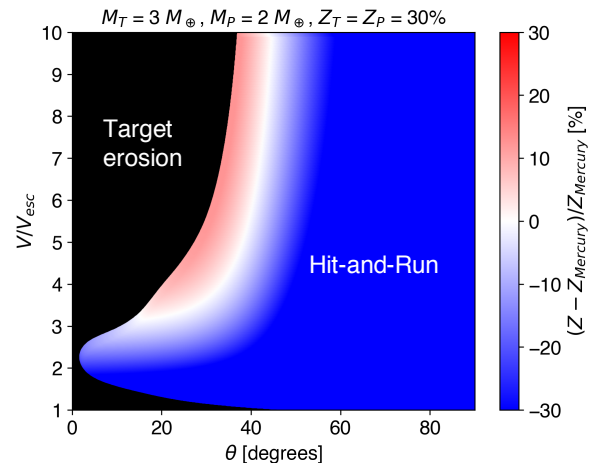


Figure 2. Difference between the core-mass fraction  $Z$  of the second remnant of a hit-and-run collision between super-Earths and that of Mercury ( $Z_{\text{Mercury}} = 70\%$ , [1]) as a function of the impact's angle and velocity (the latter in unit of mutual escape velocity  $V_{\text{esc}}$ ). White and red areas is where  $Z \geq Z_{\text{Mercury}}$ . In the black regions, the second-remnant does not exist. The symbol  $M_{\oplus}$  means 1 Earth's mass.  $T$  = target,  $P$  = projectile.

remnants occur at the boundary between the hit-and-run region and the region of target erosion (see labels in Figure 2), consistent with the findings in Fig. 3, right panel of [8] for planets less massive than Earth. We are currently using the machine-learning model to investigate whether similar giant-impacts can make Psyche-like and Mercury-like planets too, and which are the most likely values of the 6 parameters for achieving each of these outcomes. This theoretical work will help interpret data by the NASA Psyche and ESA BepiColombo missions to (16) Psyche and planet Mercury, respectively, and of exoplanets.

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