ORBITAL INSTABILITIES AS THE ORIGIN OF IRON-RICH PLANETARY BODIES.

S. Cambioni[1], B. P. Weiss[1], R. Melikyan[2], A. Emsenhuber[3], E. Asphaug[2], K. Volk[2,4], J. B. Biersteker[1]. [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2]Lunar and Planetary Laboratory, University of Arizona, USA [3]Ludwig-Maximilians-Universität München, Germany, [4]Planetary Science Institute (cambioni@mit.edu).

Abstract. Measurements of exoplanetary masses and radii show that ~20% of known rocky exoplanets have higher density than that expected from the galactic abundance of rock-forming elements [e.g., 1]. These dense "super-Mercury" planets have iron contents of ~70% by mass [2]. Like planet Mercury [2], super-Mercuries could be remnants of planets whose mantles were eroded by giant impacts [e.g., 3]. However, it is unknown whether giant impacts sufficiently energetic to erode the mantle of super-Earths are likely to occur. Here we report simulations of observed compact super-Earth systems with orbital periods < 100 days undergoing orbital instabilities that lead to formation of super-Mercuries through giant impacts. We postulate that, after formation of the precursor planets in these systems, they enter a metastable state that eventually transitions into a period of unstable orbits leading to giant impacts. Provided that such an instability occurs, we find that the probability that a compact super-Earth system transforms into a single super-Mercury planet is 4-17% (95% confidence level), consistent with the exoplanetary observations that ~7% of super-Earths are super-Mercuries without detected companions.

Introduction. Dense bodies like planet Mercury and asteroid (16) Psyche may be the cores of protoplanets whose mantle was stripped by giant impacts [e.g., 4]. Giant impacts between super-Earths may also erode mantle materials if the impact energies are sufficiently high, forming super-Mercuries [e.g., 3]. After gas disk dispersal, models of both in-situ formation and formation followed by inward migration predict a final phase of giant impacts; however, these events are mainly accretionary and do not form super-Mercuries [5, 6, 7]. Planets may also experience giant impacts billions of years after formation if their orbits become unstable. Multi-planet systems with orbital periods smaller than 100 days (which occur at a rate of ~30-50% of the FGK spectral-type stars [8]) are thought to lie close to instability [9]. Dynamical instabilities are expected to occur at a significant rate in such systems, leading to giant impacts at velocities ≤ 3.3 times the mutual escape velocity, v_{esc}, of the colliding bodies [10]. This led to the proposal that Mercury in our solar system may be the remnant of a super-Earths system that went unstable [10].

Hypothesis and methodology. We build upon the work by [10] to test the hypothesis that super-Mercuries form during late orbital instabilities of tightly-packed super-Earth systems. This hypothesis is supported by computational models of giant impacts (e.g., [3]) showing, for example, that a head-on collision at 3.3 v_{esc} transforms a 4-$M_\oplus$ planet with Earth-like composition into a super-Mercury by eroding its mantle. To simulate the effect of off-axis collisions and collision chains, we developed a model that statistically evolves an observed system of super-Earths through giant impacts given the observed planetary radii and semi-major axis values and the mass of the central star as input. For the planets, we assume an initial core-mass fraction of 30% (corresponding to an iron-to-magnesium weight ratio close to the galactic value [11]) and use the model by [12] to convert planetary radii from transit data into planetary mass. At each step of a collision chain, two planets are randomly sampled from the population of planets in the system and undergo a giant impact. The post-collision remnants are modeled as one planet in the case of accretion/erosion and two planets in the case of hit-and-run collisions. We predict the planetary masses and core-mass fractions of the remnants using a machine-learning model trained to mimic the outcome of expensive, high-resolution hydrodynamic simulations of giant impacts as in [13]. We use additional machine-learning algorithms to predict the orbital semimajor axes and eccentricities of the remnants and the masses of two smaller-scale remnants representing the debris. The input of the machine-learning models are the masses and core-mass fraction of the colliding bodies, and the collision angle and velocity. The angle is randomly sampled from the expected $\mathrm{d}P \sim \sin(2\theta)\,\mathrm{d}\theta$ distribution. The relative collision velocity is randomly sampled from a distribution of velocities adapted from that of [10], who modeled instability of tightly-packed systems using N-body simulations. Collisions involving bodies with mass less than 10^{-4} $M_\oplus$ with impactor-to-target mass ratio less than 0.05 are assumed to be perfect mergers. Ejection from the system is assessed by tracking the evolution of the bodies' eccentricity.

Case study. Here we investigate whether super-Mercuries without detected companions, which we estimate to occur at a rate of $\eta_{\mathrm{obs}} \sim 7\%$ (Table 1), formed as a result of orbital instabilities of tightly-packed super-Earth systems. We run the aforementioned collisional model for 10 tightly-packed super-Earth systems in the catalog of [14] until a single planet survives. The planets in the systems have mutual orbital spacings less than 10 mutual Hill radii (the lower boundary for instability found by [15]) and are expected to have negligible gaseous envelopes (planets with radius < 1.6 $R_\oplus$ [1], for which our machine-learning giant-impact model is the most applicable [13]). For each of the 10 systems, we run the collisional evolution model 1,000 times to get the range of plausible outcomes from the model for the mass and density of the final single planet. We compute the occurrence rate of super-Mercuries, η_{SM}, as the number of final planets whose bulk density is above the upper limit of planetary bulk density expected from galactic abundances of rock-forming elements ([1]; Figure 1). The metric of success is that η_{SM} matches η_{obs} within uncertainties.

Our preliminary results (Figure 1) show that the probability that single super-Mercuries form is $\eta_{SM} = 4 – 17$ % (95% confidence level). This was computed by bootstrapping the 1000 values of η_{SM} for each of the 10 planetary systems with a 20% leave-out rate. This range of η_{SM} is consistent with η_{obs} = 7% (Table 1), supporting the hypothesis that super-Mercuries may be the collisional remnants of orbital instabilities of tightly-packed systems of super-Earths. Future work will focus on testing the robustness of this result to model assumptions, exploring its applicability to systems in which super-Mercuries have planetary companions, and running *N*-body simulations for some systems assuming initial eccentricities and inclinations.

Discussion. The link between dynamical excitation of a planetary population and formation of iron-rich planetary bodies may be a general process of planet formation. Ref. [16] proposed that giant-planet migration produced a relatively short-lived spike in impact velocities lasting ~0.5 Myr, linking this to the formation of the CB (Bencubbin-like) metal-rich carbonaceous chondrites in an impact vapor-melt plume. Asteroid (16) Psyche — the target of a future NASA mission — may be the core of a planetesimal that lost its mantle in giant impacts [4], but mantle stripping requires $v_{coll} >> v_{esc}$ at typical impact angles $\theta \sim 45^\circ$. Such collisional velocities are rare during the end stage of terrestrial planet formation [17], but *N*-body simulations indicate that many planetary systems are metastable and can experience later periods of instabilities [10]. If the link between orbital instability and iron-rich bodies is verified, then we can use the occurrence rates, masses, radii, and orbits of super-Mercuries to constrain whether observed planetary systems experienced orbital instabilities and study the physics of such processes.

References: [1] Unterborn, C. T., et al. (2022) *arXiv: 2212.03934*. [2] Ebel, D. S., & Stewart, S. T. (2018). In *Mercury: The View after MESSENGER,* 497-515. [3] Reinhardt, C., et al. (2022). *MNRAS*, *517*(3), 3132-3143. [4] Asphaug, E., & Reufer, A. (2014). *Nat. Geo.*, *7*(8), 564-568. [5] Scora, J., et al. (2020). *MNRAS*, *493*(4), 4910- 4924. [6] Poon, S. T., et al. (2020). *MNRAS*, *491*(4), 5595-5620. [7] Esteves, L., et al. (2022). *MNRAS*, *509*(2), 2856-2868. [8] Mulders G. et al. (2018), AJ , 156, 24. [9] Pu, B., & Wu, Y. (2015), ApJ, 807, 44. [10] Volk, K., & Gladman, B. (2015). *ApJL*, *806*(2), L26. [11] Hinkel, N. R., et al. (2014) *AJ*, *148*(3), 54. [12] Weiss, L. M. & Marcy G. W. (2014) *ApJL*, 783, 1, L6. [13] Cambioni, S., et al. (2022) *LPI Contributions* 2678: 1979. [14] Weiss, L. M., et al. (2018) *AJ* 155.1:48. [15] Chambers, J. E., et al. (1996). *Icarus* 119.2: 261-268. [16] Johnson, B. C., et al. (2016) *Sci. Adv.* 2.12: e1601658. [17] Chambers, J. E. (2013). *Icarus*, *224*(1), 43-56.

Single planet	**Radius ($R_\oplus$)**	**Mass ($M_\oplus$)**	**Density (g/cm^3)**
Kepler-78	1.12 ± 0.11	1.97 ± 0.54	7.7 ± 3.1
L168-9	1.39 ± 0.09	4.60 ± 0.56	9.4 ± 2.2
K2-131	1.50 ± 0.07	6.30 ± 1.40	10.3 ± 2.7
Kepler-99	1.48 ± 0.08	6.15 ± 1.30	10.5 ± 2.8
GJ 367	0.72 ± 0.05	0.55 ± 0.08	8.1 ± 2.2
HD137496	1.31 ± 0.06	4.04 ± 0.55	9.9 ± 1.9

Table 1. Parameters and their 1-sigma uncertainties for the 6 super-Mercury planets that do not have companions, ~35% of the 17 super-Mercuries identified by [1]. $\oplus$ = Earth. Based on this limited sample, we estimate that the occurrence rate of single super-Mercuries is η_{obs} ~ 7% by multiplying 35% times 20%, where 20% is the abundance of super-Mercuries among super-Earths [1], caveat that observed single super-Mercuries may share the system with undetected companions.

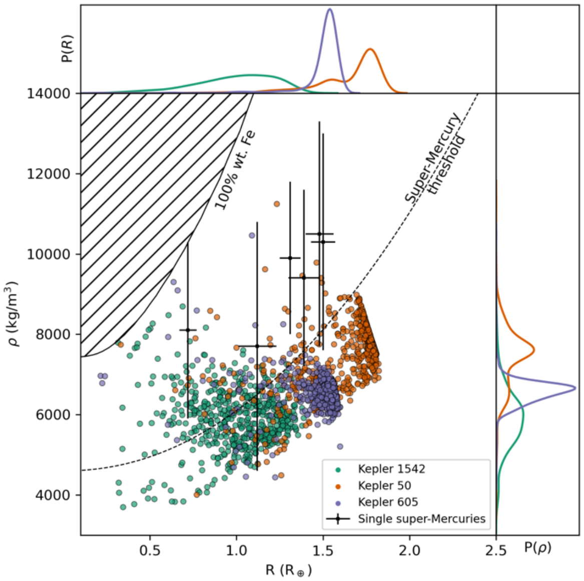

Figure 1. Density, *ρ*, versus radius, *R*, of the final planets resulting from the collisional evolution of three sample super-Earth systems. Each colored point is only for simulations ending in one planet. The super-Mercury threshold in *ρ*-*R* coordinates from [1] is plotted as a dashed curve. The normalized marginal distributions are for *ρ* (right) and *R* (top). The single detected super-Mercuries are from Table 1 (crosses denoting 1-sigma uncertainties). The hatched area is the forbidden region where a planet would have iron content > 100%.