STRIKE WHILE THE IRON IS HOT: GIANT IMPACTS AND VAPORISATION AS THE KEY TO FORMING DENSE, IRON-RICH WORLDS?

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Introduction: Mercury, the smallest of the terrestrial planets, has always been somewhat mysterious. It is only around half the mass of Mars and yet has almost the same surface gravity thanks to its massive core, which at around 70% of its mass is proportionately more than twice as large as Earth's (∼32%) or the other terrestrial planets'. As the number of known exoplanets continues to grow, a new class of worlds is emerging: super-Mercuries, planets comparable to or more massive than Earth, but with high core-mass fractions (CMF) like Mercury, especially relative to values predicted from their host-star's Fe/Mg molar ratio [e.g., 1].

CMF will naturally track with the Fe/Mg ratio in the planet's stellar system [e.g, 2, 3]. If a planet's composition matches its star's, then $\mathrm{CMF} = [1 + 1.72/(\mathrm{Fe/Mg})]^{-1}$. Earth's CMF of 0.32 corresponds exactly to the value $\mathrm{Fe/Mg} = 0.81$ observed in the Sun [4, 5]. Because stellar $\mathrm{Fe/Mg}$ values vary, one might expect a range in planetary CMFs, as illustrated in Fig. 1 using the $\mathrm{Fe/Mg}$ ratios for 7677 stars in the *Hypatia* catalogue [6], assuming all Fe in a planet resides in its core. From this we would expect almost all planets to have CMFs in the range 0.15–0.5 (grey band in Fig. 1 bottom panel). Yet, among observed exoplanets with good densities (uncertainties $< 50\%$), 22 are—like Mercury—more dense than the maximum expected based on the range of stellar $\mathrm{Fe/Mg}$ (red crosses in Fig. 1 bottom panel). These planets have CMFs as high as Mercury, but have radii 0.7—1.6 $R_\oplus$, orbital periods 0.3—32 days, and orbit stars between 0.45 and 1.45 $M_\oplus$.

How did super-mercuries form, and what does their formation share with Mercury in our own Solar System?

Giant impacts for Mercury and super-mercuries? Because of previous work to understand the origin of Mercury, hypotheses already exist for the formation of super-mercuries. The most commonly invoked scenario for the formation of Mercury is that it suffered a giant impact energetic enough to strip away a large fraction of its lower-density silicate mantle [9, 10]. Giant, planetary-scale impacts are a commonly accepted feature of the late stages of terrestrial planet formation. These can be either accretionary or erosive, [11, 12]. When impacts are erosive, numerical simulations show that material is generally removed from the outer layers of the body first, i.e., the mantle, leaving proportionally more core, raising CMF [e.g., 12, 13, 14]. This model has not been universally accepted because Mercury is expected to reaccrete

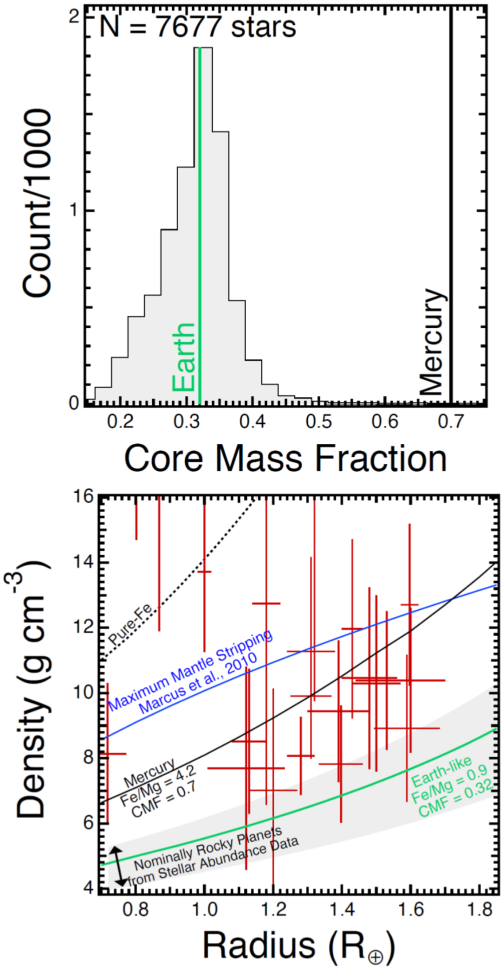

Figure 1: (*Top*): Histogram of planet CMFs if rocky planets matched their host-stars' compositions, for 7677 stars with known abundances in the *Hypatia* catalogue. (*Bottom*): Bulk density vs. radius for 22 exoplanets (red crosses are data from IPAC exoplanet archive) denser than typical stellar abundances would imply (green curve traces $\mathrm{Fe/Mg} = 0.9$; gray band denotes $\pm 3\sigma$ uncertainties [7]). Black curve denotes density vs. radius for planets with Mercury-like $\mathrm{CMF} = 0.7$ (equivalent to $\mathrm{Fe/Mg} = 4.2$). Dashed curve denotes a pure Fe planet. Curves computed using ExoPlex code [7]. Blue curve denotes density after a single impact on a planet with $\mathrm{CMF} = 0.32$, using a theoretical upper limit to mantle stripping [8].

almost all of the ejected debris. This is true even if the ejecta emerge as vapour (or super-critical fluid) that coalesce into millimetre-sized droplets subject to Poynting-Robertson drag [15]. However, if the giant impacts took place in a system's first $\sim 10^7$ yr, when residual protoplanetary disk gas remained, the droplets could easily be lost by aerodynamic drag [16].

Another potential objection to mantle-stripping giant impacts explaining super-mercuries is that there is a maximum amount of mantle that can be stripped during a single impact [8]. However, it is certainly plausible for some planets to suffer more than one giant impact. Depending on the fraction of mantle ejected in a collision, and the fraction that emerges as vapour and is not reaccreted, among other factors, a wide variety of outcomes and final CMFs are possible, as depicted in Figure 2. Because of their orbital distances, super-mercuries generally experienced faster impacts, which helps increase CMF.

Conclusion: Super-mercuries represent test cases where we can investigate ideas about Mercury's formation in systems with different parameters. Likewise, formation of super-mercuries is informed by modelling of Mercury's origin.

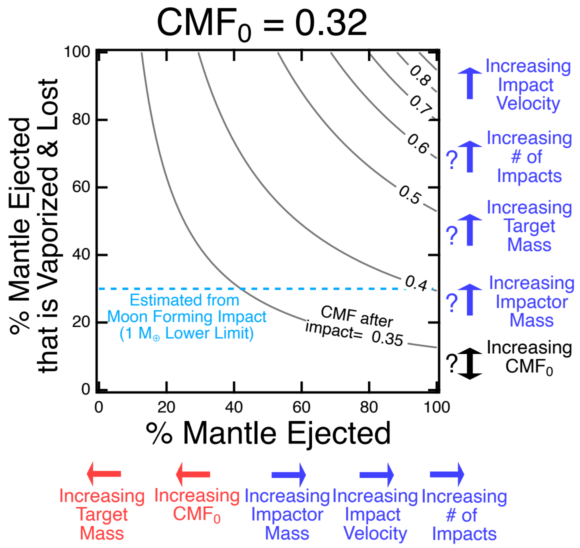

Figure 2: Contours of final CMF after an impact, as a function of the percentage of mantle ejected and the percentage of that ejecta that is vaporised, for planets with initial CMFs of 0.32. Different factors to be included in our model will likely lower (red) or increase (blue) the amount of material ejected or vaporised. Those factors with question marks are those not yet included in any super-mercury formation and vaporisation models. The dashed blue line denotes the 30% of the mantle estimated to have vaporised during the Moon-forming impact [17] and represents a likely lower limit for 1 M$_\oplus$ targets.

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