REVISITING THE GIANT IMPACT MODEL FOR MERCURY. S.J. Desch[1], A.P. Jackson[1], C.T. Unterborn[1], F.M. McCubbin[2], [1]School of Earth and Space Exploration, Arizona State University, Tempe AZ 85287. [2]Astromaterials Research and Exploration Science, Johnson Space Center, Houston TX 77058. steve.desch@asu.edu

Introduction. Mercury's core is 69-77% of its mass [1]. This has been explained alternatively as Mercury having suffered a giant impact that stripped its mantle [2,3], or extensive evaporation of its silicate mantle [4,5], or formation in a region with excess metal [6-8]. As reviewed by [9], no current model is entirely satisfactory. Determining the cause of Mercury's large iron fraction would inform planet formation models.

The *MESSENGER* mission measured Mercury's surface abundances; combined with modeling, these yield mantle compositions. Consistent with formation near the Sun, Mercury's surface is enriched in the refractory elements Ca, Al, and Ti (relative to Mg and to Earth); but Mercury's surface also is highly enriched in the volatile elements Na and K; e.g., the northern volcanic plains lavas have 6-7wt% Na_2O, and 0.20 wt% K_2O [10,11]. Its mantle is enriched both in refractory elements (Ca, Al, Ti) and volatile elements (Na,K) (**Table 1**). Using mantle abundances derived from the IcP-HCT lavas [12], and comparing to pyrolite Earth [13], the abundances of Ca, Al and Ti relative to Mg are about 2.7 times terrestrial values, while the abundances of Na and K relative to Mg are 10 and 4 times Earth's. These abundances are not correlated with volatility. They may reflect loss of Mg, but Na and K are more enriched than Ca, Al, and Ti, and it isn't clear how Mg would be preferentially lost (unlike Si, it is not expected to enter Mercury's core). Mercury's elemental abundances are as mysterious as its large core fraction.

The giant impact model suffers limitations. A low impact parameter ($b \approx 0.2$-0.3) and moderate impact velocity (v_{imp} ~15 km/s) can strip the mantle and yield Mercury's high core fraction [14], but such head-on collisions are unlikely, and such impact speeds (~1/3 Mercury's velocity), require impactor eccentricity ≈ 0.5 hard to justify [15] and difficult to reconcile with the low-excitation dynamical state of today's inner solar system [16]. The main limitation is that Mercury should reaccrete the ejecta after the impact. To lose material, ejecta must melt and coalesce into ~cm-sized droplets that can be lost to the Sun, e.g., by Poynting-Robertson drag [3], but even so Mercury will reaccrete > 35% of the material, or more if the optical depth of the debris ring is considered [17]. Even if giant impact models could explain the high iron fraction, they currently do not address the enrichments in volatiles.

Here we show that if the giant impact occurred at ~5 Myr into solar system history, the limitations of the giant impact model are removed. Sufficient nebular gas remains to cause aerodynamic drag of particles into the Sun. We also show that decompression vaporization will lead to preferential loss of $MgSiO_3$, possibly explaining the enrichments in Ca, Al, Na, etc.

X	Earth	NSP Lava	$(X/Mg)_{NSP}$ / $(X/Mg)_E$	IcP-HCT Lava	$(X/Mg)_{ICP}$ / $(X/Mg)_E$
Mg	22.8	8.38		16.76	
Si	21.0	27.44	3.56	24.64	1.60
Fe	6.26	0.03	0.013	0.03	0.007
Ca	2.53	4.15	4.46	5.20	2.80
Al	2.35	7.30	8.45	4.65	2.70
Ti	0.12	0.24	5.44	0.24	2.72
Na	0.27	5.2	52.4	2.04	10.3
K	0.024	0.17	19.3	0.066	3.74

Table 1: Elemental abundances (wt%) of pyrolite Earth [13] and Mercury's mantle as inferred from northern smooth plain (NSP) and inter-crater plains, heavily-cratered terrains (IcP-HCT) lavas [12], plus abundances relative to Mg and Earth.

A Giant Impact at 5 Myr? We propose that a Mars-sized proto-Mercury suffered a giant impact at ~ 5 Myr into solar system history. Such an early formation of (proto-)Mercury, while solar nebula gas remained, could not have been considered until recently; but now strong evidence suggests rapid growth of Moon- to Mars-sized planetary embryos in a few Myr by 'pebble accretion' [18]. Detailed models [19] predict the existence of dozens of Mars-sized embryos throughout the inner disk by 2 Myr. Mars itself has been constrained by Hf-W dating to have accreted most of its mass between 1 and 3 Myr [20]. Moreover, the collision that produced CB/CH chondrites took place at t ≈ 4.8 Myr [21], and the ureilite parent body was catastrophically disrupted soon after 5 Myr [22], suggesting a dynamical instability at this time, possibly due to the outward migration of Jupiter [23,24]. It is quite plausible that proto-Mercury could have formed and been struck by another planetary embryo, at about 5 Myr.

Fate of Vaporized Ejecta. All models (e.g., [2]) of the fate of ejecta from the giant impact neglect the role of gas, but at 5 Myr most protoplanetary disks are transition disks, with some gas in their innermost few AU [25]. Detailed models of the solar nebula suggest it was depleted of gas inside 3 AU, but that gas certainly existed beyond Jupiter until at least 4 Myr, probably longer [24]. Gas accreting from the outer disk at a mass accretion rate as low as 10^{-10} $M_\odot$/yr (appropriate for disks ~10 Myr old [26]) and turbulent viscosity parameter even as high as $\alpha = 0.05$ would yield surface density >1 g cm^{-2} and gas density $>10^{-12}$ g cm^{-3}. From Figure 4 of [27], 1 cm particles at 1 AU radially drift at $\sim 10^4$ cm/s, or 0.02 AU/yr, so any ejecta condensed into cm-sized particles spiraled into the Sun in tens of years, far faster than the ~3 Myr to reaccrete the ejecta [2]. In contrast, ~km-sized fragments of proto-Mercury's mantle would take $> 10^2$ Myr to inspiral, and were largely reaccreted by Mercury. An impact at 5 Myr solves the reaccretion problem: any vaporized ejecta is almost entirely lost by aerodynamic drag.

Composition of Mercury. A proto-Mercury with mass 2.25 M_{Merc}, formed in 1-3 Myr, is predicted to differentiate, form a magma ocean, and then see the magma ocean crystallize, by 5 Myr [28]. Assuming an Earth-like bulk composition, the layers of proto-Mercury should be as found by [29], depicted in **Figure 1**. In the lower half of the mantle are: olivine [ol], Mg_2SiO_4; and orthopyroxene [opx], $MgSiO_3$. In the top half of the mantle are a mix of: olivine; Ca-bearing clinopyroxene [cpx], $(Ca,Mg)SiO_3$; plagioclase [plag], $NaAlSi_3O_8$-$CaAl_2Si_2O_8$; garnet [grnt], $Ca_3Al_2(SiO_4)_3$; and, at the surface, opaques like Ti oxides. Significantly, Mg wt% increases with depth. The top layers are densest but we assume mantle overturn takes > 5 Myr.

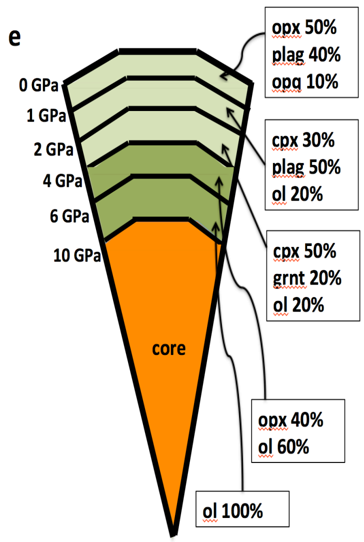

Figure 1: The layers of proto-Mercury at 5 Myr, after magma ocean crystallization but before mantle overturn. The deep mantle is primarily $Mg_2SiO_4 + MgSiO_3$.

We presume the cores of the two bodies merge during the impact. We hypothesize that material ejected from the hottest, deepest layers of proto-Mercury undergoes transition to a supercitical fluid and recondenses as cm-sized droplets. This preferentially removes ol+opx material rich in Mg and Si. Material from the uppermost few GPa (depending on the thermal gradient) of the mantle is ejected as km-sized fragments and ends up largely reaccreted, allowing Mercury to retain much of its Ca (from cpx), Na and Al (from plag), and Ti (from opaques), which would explain their enrichments relative to Mg. We further suggest that Si sequestered in proto-Mercury's core at high pressure could be reintroduced to the mantle after the collision, raising the Si/Mg ratio, as the solubility of Si in Fe metal is sensitive to pressure [30]. The oxidation of Si^0 in the core to SiO_2 components in the mantle also would reduce the oxygen fugacity of Mercury's mantle (likely through reduction of FeO to Fe^0) and could explain the enigmatically low fO_2 of Mercury's mantle.

Summary. The sequence of events we hypothesize led to Mercury today is depicted in **Figure 2**: a) formation of proto-Mercury as a planetary embryo, then magma ocean crystallization but no overturn; b) impact at ~5 Myr, with ejection of upper mantle as fragments, and the lower mantle as cm-sized droplets (due to decompression vaporization), followed by loss due to aerodynamic drag; c) reaccretion of the upper mantle; d) loss of Si from the core due to the lower pressures.

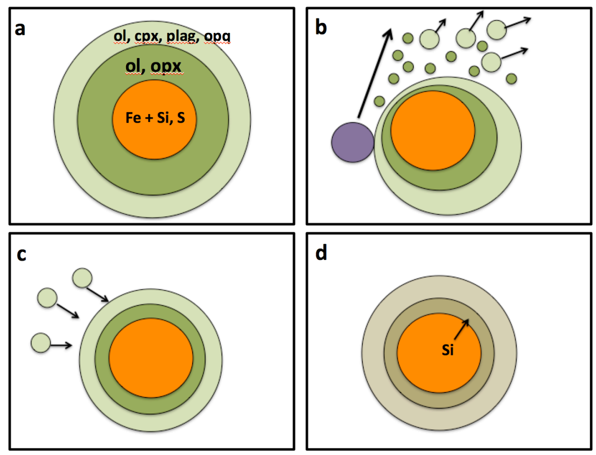

Figure 2: Our hypothesis for Mercury's formation.

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