Abundance and Habitability of super-Mercuries. S.W. Parman[1], A.J. Evans[1], M.B. Weller[1], C.T. Reinhard[2], D.E. Ibarra[1], E.C. First[1] and B.A. Anzures[1], [1]Dept. Earth, Environmental, and Planetary Sciences, Brown Univ., Providence, RI, 02906. stephen_parman@brown.edu [2]School of Earth and Atmospheric Sciences, Georgia Inst. Tech., Atlanta, GA 30332.

Introduction: Mercury is an extreme end-member among the terrestrial planets. In particular, it formed at a substantially lower oxygen fugacity (fO_2) than the Earth, Moon, Mars or Venus (Figure 1; [1,2]). The low fO_2 has affected all aspects of Mercury's evolution, from the size of its core, to the viscosity of its mantle, to the composition of its crust [3]. At such low fO_2, exotic, reduced sulfides such as oldhamite (CaS) and niningerite (MgS) become prominent phases. The bonding of Ca and Mg with S happens in response to the decreasing availability of oxygen [4], and results in extraordinarily high S solubilities in silicate melts (up to 15 wt%). And indeed, Mercury's volcanic surface contains 2-4 wt% S, probably as some mixture of CaS and MgS [5]. Because Mercury is so close to the Sun, it was predicted to be volatile-depleted, relative to the other terrestrial planets. But it is actually quite volatile-rich, with Earth-like K/U and high Na contents in lavas, not to mention the high S [2]. Moreover, pyroclastic volcanism is quite ubiquitous [6]. Apparently, even under adverse conditions, Mercury was able to hold on to a substantial volatile reservoir in its interior. However, Mercury was too small to hold on to an atmosphere. But what if it were larger?

Could there be exoplanets as reduced and sulfide-rich as Mercury, but large enough to retain an atmosphere? Would such super-Mercuries be habitable? To address this, we explore three questions: 1) How abundant are super-Mercury exoplanets?, 2) What sort of gases would be emitted by volcanism into the atmosphere? and 3) Are there plausible scenarios in which super-Mercuries could host liquid water oceans on their surfaces?

Question 1: **How abundant are reduced sulfide planets (super-Mercuries)?** Mercury is thought to have obtained its low oxygen fugacity because of the high abundance of carbon-rich dust that gathered close to the early Sun, where Mercury accreted [7]. The high C/O ratios produced abundant CO, which lowered oxygen activities. Condensation models for the enstatite chondrites suggest that C/O ratios above 0.8 are required to stabilize the reduced sulfides MgS and CaS [8]. However, exoplanet evolution models have generally not predicted the existence of sulfide-rich, Mercury-like planets (though see [9]), despite one existing in our own solar system! Above C/O=0.8, such models have typically predicted that carbon-rich carbide planets would form [10]. Given the paucity of experimental data at such reduced conditions, it is perhaps not surprising there is discrepancy in the current predictive models. More data is needed. What is clear is that reduced sulfide planets would likely form at C/O ratios intermediate between that of Earth-like planets and carbide planets. The exact boundaries between these regimes are not well defined at this time.

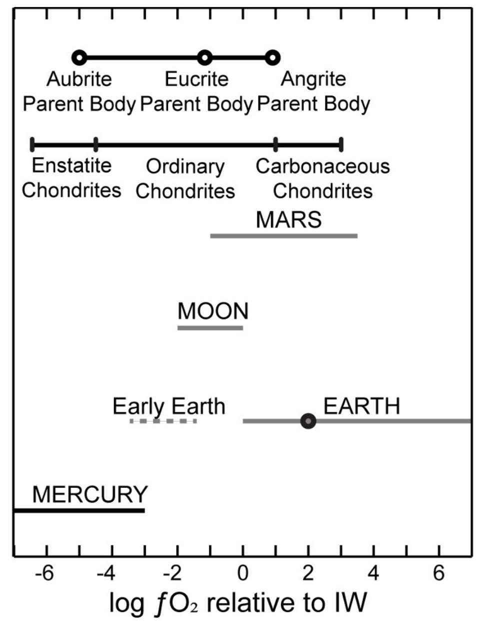

Figure 1. *Mercury is more reduced than all the other terrestrial planets, including the Moon. Only the enstatite chondrites and aubrite parent body have as low oxygen fugacity.*

A related but complementary question is what range of host star C/O compositions could produce super-Mercuries? Our solar system, with a C/O ratio of only ~0.58 [11], mostly produced Earth-like planets, but C/O varied enough to produce one (small) reduced sulfide planet at the very inner edge of the disc. Our system seems to be near the lower bound of C/O ratios that can form reduced sulfide planets. We hypothesize that the enrichment of carbon-rich dust within protoplanetary discs could allow Mercury-like planets to form around stars with C/O ratios of 0.6 to at least 0.8. Taking this as a conservative range, and comparing it to the C/O ratio of exoplanet host stars, we see that more than 50% of the systems could host reduced sulfide exoplanets (Figure 2). Indeed, it may be that such sulfide exoplanets are more common than the carbide planets!

Question 2: **What gases would be emitted by volcanos on super-Mercuries?** Equilibrium models suggest N_2, CO, S_2, CS_2, S_2Cl, Cl, Cl_2 and COS could be the major volcanic gases on planets as reduced as Mercury

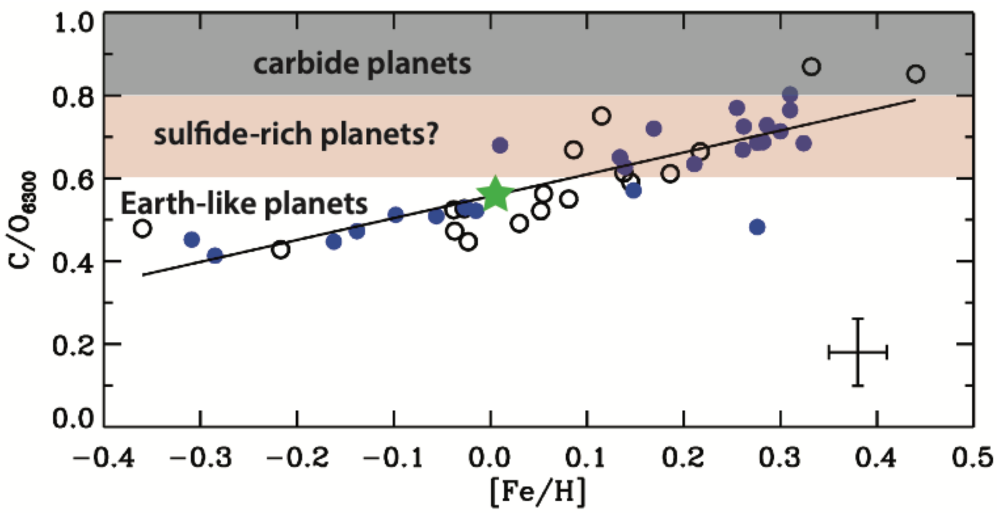

Figure 2. *C/O ratios of exoplanet host stars (blue filled circles) and stars with thin planetary discs (open circles; after [11]). Star indicates C/O ratio of the Sun. Due to the process of dust enrichment, host stars with C/O ratios between 0.6 and 0.8 may host super-Mercuries (red area). Host stars with higher C/O ratios may harbor carbide planets (gray area).*

[12]. While S is highly abundant, MgS and CaS are very refractory, with melting points above 2000 ºC. Thus most S dissolved in silicate melts should exsolve as sulfide liquids or crystals during eruption and cooling. However, there is so much dissolved S, that even if a small fraction formed a gas species, it would be substantial. What is clear is that H_2O and CO_2, primary gases in Earth-like planets, are unlikely to be abundant. Indeed, the reduced sulfides CaS and MgS react strongly with H_2O to form H_2S gas and sulfuric acid. If H_2O is not emitted by volcanism, can a super-Mercury ever have a liquid water ocean?

Question 3: **Could water oceans exist on super-Mercuries?** Planetary atmospheres are built from a number of components, including primordial nebular gases, volcanic gases from the interior and volatiles from late accreting materials. In our own solar system, the rearrangement of Jupiter's orbit likely hurled large amounts of H_2O-rich outer solar system material into the inner solar system. The 'watering' caused by such orbit adjustments could deliver enough water to overcome the intrinsic low fO_2 of a super-Mercuries crust, and yield a liquid water ocean [13]. If so, subsequent volcanic eruptions would react quite strongly with the ocean, producing high porosity in the lavas, and high S contents in the ocean and atmosphere. Under such conditions, the energy gradient between the highly reduced-S-rich lavas and the more oxidized hydrosphere would be a tremendous source of energy for chemotrophic life. Though such life would have to be very tolerant of high S concentrations, and likely, wide swings and gradients in the oxygen fugacity.

Conclusions: Reduced, sulfide-rich 'super-Mercuries' should be common around host stars with C/O above 0.6. Based on observations of Mercury, such planets should be rich in a range of volatiles, including C, N, S, Cl, Na and K. H_2O and CO_2 are not expected to be stable, and H in any form should not be abundant. Introduction of ice-rich material from beyond the snow line could provide a pathway to having liquid water oceans on super-Mercuries. The redox gradient between the interior of super-Mercuries and their oceans will be much larger than on Earth, and could provide an abundant energy source for life, if the high levels of S are not fatal.

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