ASSESSING THE ABUNDANCE OF SUPER-MERCURIES AND THEIR HABITABILITY

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Introduction: Mercury formed at an oxygen fugacity more than 3 log units below the iron-wüstite buffer (<IW-3, [1]). The low fO_2 dramatically effects both chemical and physical properties of melts and solids, and set Mercury on an evolution path quite distinct from the other terrestrial planets. This includes a massive metallic core (80% of radius), incredible amounts of S on its surface and little Fe in its silicates [2]. Interestingly, while Mercury's proximity to the Sun led many to predict it would be volatile-depleted, in fact it appears to have a volatile content similar to the Earth [3]. This leads to an interesting question in the context of exoplanets. If Mercury was large enough to retain its atmosphere, and was at a more hospitable distance from the Sun, what sort of atmosphere would it form? And would such super-Mercuries be habitable?

How many super-Mercuries are there? Mercury is so reduced because the protoplanetary disc near the Sun (<0.5 AU) was enriched in carbon-bearing dust. This produced a high C/O environment that forced the oxygen fugacity to be extremely low [4]. Similarly, models of exoplanets formation around high-C/O stars indicate they also should be reduced [6]. Most of these models yielded carbon- and carbide-rich planets, but did not produce Mercury-like, sulfide-rich planets. Modeling of Mercury's formation shows that between the fO_2 of Earth-like oxidized planets and highly reduced carbide planets, lies an intermediate field of stability where exotic sulfides (MgS and CaS) are stable, and sulfide-rich planets like Mercury could form [4]. Where the upper fO_2 boundary for the sulfide field is not well constrained. Based on [4], we suggest it lies above [C/O] = 0.2 dex. Our solar system appears to be close to the lower [C/O] boundary, and so we take its value to be near zero.

To search for candidate super-Mercuries, we used the Hypatia catalog of star compositions, and filtered for exoplanet host stars with [C/O] > -0.15 and for exoplanets with mass < 5 $M_\oplus$. This yields 57 potential super-Mercuries (Fig. 1a). Figure 1b shows the semi-major axis of the exoplanets (solid gray squares). Because carbon is concentrated near stars, the C/O ratio in the protoplanetary disc will increase close to the star. For a given star type, the C/O boundary between Earth-like and Mercury-like formation conditions should move to greater distances as C/O of the star increases. This is shown as a dashed line in Fig. 1b, but is schematic only, as the exact shape and position of this

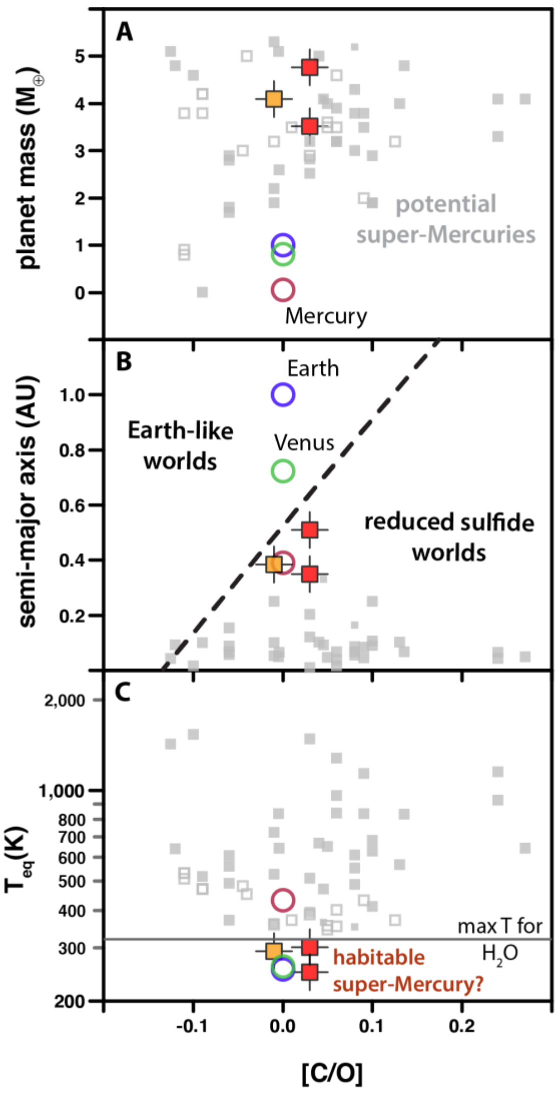

Figure 1. *Exoplanet properties (mass, orbital semi-major axis, equilibrium temperature) compared to the normalized C/O ratio of the host star ([C/O] of the Sun is 0). Data taken from the Hypatia catalog [5]. Squares are exoplanets: filled gray have semi-major axis data, open gray do not, red and orange filled have equilibrium temperatures below 340K, one estimate for the upper limit of water-based habitability [7]. Circles are Earth (blue), Venus (green) and Mercury (red). Dashed line is schematic only, and shows the boundary between Earth-like planets and Mercury-like planets. See text for more detail.*

line is not known at this point, and will vary with a number of stellar parameters. For our solar system, the boundary appears to be between the orbit of Mercury and Venus. Most of the potential super-Mercuries orbit much closer to the host-star than Mercury, and most of the host stars are Sun-like (FGK type). So it is likely that most of these exoplanets formed in areas of their protoplanetary discs that were as reducing as Mercury, Some of the exoplanets with very small orbits and host star [C/O] above 0.1 may be carbide planets.

How many of the super-Mercuries are potentially habitable? How many of the exoplanets in Figure 1 could be habitable? For water-based life, the temperature of the planet should be below 340K [7]. We calculate equilibrium temperature (T_{eq}) using the simplified equations in [8]. As we are trying to be inclusive/optimistic, we use a high, Venus-like Bond albedo of 0.75, that yields lower bounds on T_{eq}. Of the 57 potential super-Mercuries, 3 have T_{eq} less than 340 K (Figure 1c). Two (HD20794 d and e) orbit the same host star (also known as 82 G. Eridani, red squares in Fig. 1). Both of these exoplanets have higher densities than Earth, and so would be consistent with a larger metallic Fe core, as expected for reduced planets.

The other candidate is Kepler 51c. While it has a mass of 4 $M_{\oplus}$, its radius is 0.8 of Jupiter's, and so it has been called a 'super-puff'. How such planets form is debated [9]. The star is quite young (500 m.y.), so it seems plausible that Kepler 51c is a terrestrial planet with a large primary, H-rich atmosphere that it is in the process of losing. Thus it could be a young super-Mercury, which may be habitable now, or in the future as the atmosphere evolves. Thus, from a dataset of 1,309 known host stars (mostly of FGK type), which also have their compositions measured, there are 3 potential super-Mercuries that could host water-based life.

Extrapolating this to estimate how many habitable super-Mercuries exist within our galaxy, or our local region, is difficult because of the large biases in the observations, especially to planets with short periods. Using 3/1,309 as the abundance is likely to greatly underestimate the number of potentially habitable super-Mercuries. But even so, there should be about 5 million FGK type stars within 1500 ly of Earth, which should equate to at least 11,400 potentially habitable (water-based) super-Mercuries. Again, given the biases in current detection methods, we expect this greatly underestimates the real number.

What are the compositions of super-Mercury atmospheres? The speciation of volatiles at Mercury-like conditions (low fO_2, high fS) is not well understood, particularly for high-S fugacities and pressures above 1 bar. [10] and [11] used existing thermodynamic data and modeled potential gas speciation over a range of fO_2, S content, pressure and temperature. The results indicate that S_2, CO, N_2, CS_2, Cl_2, Cl and S_2Cl will be the dominant gas species emitted by volcanism. Notably, H_2O and OH are not stable at such low fO_2, and solubilities of H are low in silicate melts. So, reduced sulfide planets should have low H contents, and volcanic gases should deliver small amounts of H-bearing species to the surface. Given this, if liquid water is to be stable, and abundant, on the surface of super-Mercuries, it may need to come from somewhere other than volcanic degassing.

This could occur through migration of planet orbits [12]. For the Earth, migration of Jupiter's orbit caused inward migration of oxidized, H_2O-rich material that accreted to the more reduced material the proto-Earth initially formed from [13]. Enough water to form an ocean could be delivered to a super-Mercury by a similar process. If liquid water was present on the surface of a super-Mercury, the high amounts of reduced S in the magmas, and in their gases, could produce an abundant supply of energy for life based on S-oxidation.

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