THE HABITABILITY OF MERCURY SIZED EXOPLANETS WITH MOBILE AND STAGNANT LID TECTONIC REGIMES.

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Introduction: Over the past 30 years, a number of sub-Earth sized terrestrial exoplanets have been discovered. The smallest of these exoplanets is Kepler-37b, roughly the size of the Moon. The habitability of sub-Earth sized exoplanets are often overlooked in exoplanetary research, due to their difficulty to detect. As the prospects of observing more sub-Earth sized bodies increases with improvements in detection, it raises the question as to what conditions are necessary for these bodies to be capable of potentially hosting life.

Mobile lid tectonics are considered a fundamental component of generating and sustaining a liquid water ocean on the surface of the Earth, allowing it to become habitable. However, the amount of terrestrial like planets which express active plate tectonic regimes are likely to be considerably fewer in number than those with stagnant lids. Recent studies have shown that Earth like planets [1, 2] and super Earths [3] with stagnant lid regimes are potentially capable of producing habitable environments over geological timescales.

We examine the thermochemical evolution of Mercury sized bodies over a period of 10 billion years using stagnant lid and mobile lid convection models. We use these models to determine when planets nominally exist in a habitable regime. Accordingly, we calculate surface pressure and temperature evolution as well as the atmospheric abundance of volatiles (a proxy for habitability).

Methods: We use parametrized one-dimensional models of the planet's evolution, coupling the interior evolution of the planet to its atmosphere [4].

Solidus and liquidus temperatures are estimated using a water corrected parameterization [5]. The extraction of volatiles from the interior as melting progresses results in a feedback mechanism for the mantle viscosity and interior temperature of the planet. Importantly, melt evolution is linked to outgassing via a pressure and oxygen fugacity dependent gas speciation model [6]. For simplicity, we assume a Bulk Silicate Earth mantle composition.

Our viscosity formulation is temperature, pressure, melt fraction and water content dependent and calibrated such that an Earth like mantle with a potential temperature of 1660 K and 600 ppm of H_2O has an effective viscosity of $1.2 \cdot 10^{21}$ Pa s [7].

In addition to varying the tectonic regime using the technique outline in [7], we also vary mantle potential temperature (1400—1600 K), core fraction (0.2—0.85) and distance from the host star (0.5—1.5 AU). Temperature at the core mantle boundary is either fixed at 2000 K or is offset from the adiabatically calculated mantle temperature at the CMB by a few hundred degrees. Properties held constant between models are shown in Table 1.

Parameter	***Value***	***Units***
Thermal expansivity	$3*10^{-5}$	K^{-1}
Thermal diffusivity	$1*10^{-6}$	$m^2\ s^{-1}$
Heat capacity mantle	1400	$J\ kg^{-1}\ k^{-1}$
Heat capacity core	840	$J\ kg^{-1}\ k^{-1}$
Reference mantle density	3400	$Kg\ m^{-3}$
Reference core density	10000	$Kg\ m^{-3}$
Radius	2440	Km
Critical Rayleigh number	1100	
Ocean mass equivalent	$2.05*10^{20}$	Kg

Table 1: Fixed model parameters

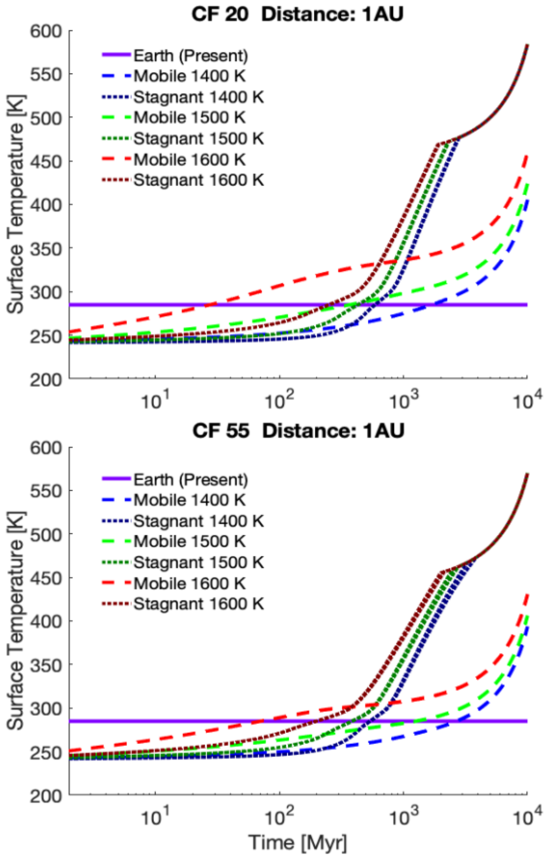

Figure 1: Surface temperature at 1 AU with core fractions of 20% (top) and 55% (bottom). Although mobile lid convection is initially faster in raising surface temperatures, stagnant lid convection results in higher surface temperatures within 1 Ga. The solid horizontal line is the global average Earth surface temperature for reference. CF — Core Fraction.

Results: Figure 1 shows how surface temperatures typically evolve through time in our models. The parameters that have the greatest influence on surface temperature are distance from the host star, tectonic regime and initial mantle potential temperature, with the latter two parameters also having the largest influence on melt productivity. The influence of initial mantle potential temperature on surface temperatures is greatest in mobile lid models with large core fractions.

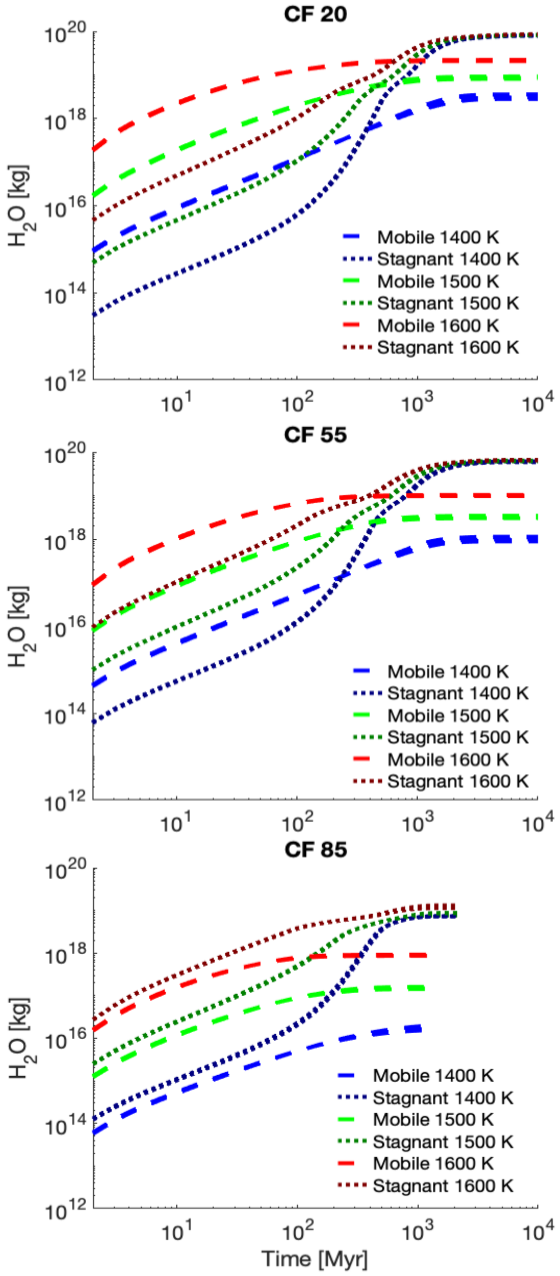

Figure 2: Cumulative water outgassed from the mantle of planets with varying core fractions of 20% (top), 55% (middle) and 85% (bottom). These three core fractions represent lunar, Earth and Mercurian core fractions respectively. Colour denotes initial mantle potential temperature.

For models with core fractions in excess of 70%, within the 10 Gyr model period, whole mantle convection ceases. This occurs in the mobile lid models first at around 9.5 Ga. Increasing the core fraction to 85%, roughly the size of Mercury's core, results in whole mantle convection cessation at approximately 1 Ga for mobile lid models and 2.5 Ga for stagnant lid models. Importantly, varying core temperature and initial mantle potential temperatures can increase the longevity of convective processes in the mantle by a few 10s of millions of years. However, greater lifetimes for these convecting mantles would require changes in mantle composition in addition to changes in general thermal parameters.

Figure 2 shows the total mass of outgassed H_2O for our models. Mobile lid tectonic regimes are most efficient at outgassing volatiles in the first billion years of model run time when core size is small. Increasing initial mantle temperature results in a greater mass of outgassed material however, the effect of this initial temperature difference becomes less significant over time, particularly for stagnant lid models. The maximum amount of outgassed H_2O is approximately 0.4 ocean mass equivalents for the stagnant lid models with a 20% core fraction. Mobile lid models typically outgas one to two orders of magnitude times fewer volatiles under the same conditions. This outgassing produces a maximum modeled atmospheric pressure of roughly 100 bars, assuming no loss mechanism, for stagnant lid models and 20 bars for mobile lid models, although these models more typically produce atmospheres of only a few bars.

Conclusions: For Mercury sized exoplanets with Earth like compositions, we observe that stagnant lid convection models are more adept at outgassing volatiles over longer timescales than mobile lid models, increasing the likelihood that these planets are capable of sustaining liquid water at the surface. With increasing core mass fraction, the longevity of these convective regimes decreases significantly, in the absence of additional sources of internal heating. Initial mantle potential temperature plays a more significant role in the earliest stages of planetary evolution and in mobile lid regimes.

References: [1] J. F. Bradford (2019) The Astrophysical Journal, 875, 72. [2] N. Tosi *et al.*, (2017) Astronomy & Astrophysics, 605, A71. [3] C. Dorn *et al.*, (2018) Astronomy & Astrophysics, 614, A18. [4] M. B. Weller & S. W. Kiefer (2020) J. Geophys. Res.: Planet, 125(1). [5] R. F. Katz *et al.*, (2003) Geochemistry Geophysics Geosystems, 4(9), 1073. [6] F. Gaillard & B. Scaillet (2013) Earth and Planetary Science Letters, 403, 307-316. [7] M. B. Weller *et al.*, (2022) LPSC Abstract 2328.