Habitability of Sub-Earth Sized Exoplanets in Mobile and Stagnant Lid Tectonic Regimes

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Introduction: As our methods of detecting exoplanets have improved, an increasing number of sub-Earth sized terrestrial exoplanets have been observed [1]. Sub-Earth sized planets are defined as having a mass substantially less than that of the Earth and Venus [2]. Two such planets exist in our own solar system, Mars and Mercury. The smallest detected exoplanet at present has a radius between that of Mercury and the Moon [1]. Although planets of the size of Mercury (surface gravity of 3.7 m/s) or smaller are typically considered to be less likely to retain an atmosphere due to low surface gravity values. Modelling suggests that planets with a surface gravity as low as 1.48m/s have the potential to harbour life if only for a brief period of time [3]. While sub-Earth sized planets may not be capable of retaining an atmosphere for several billion years, during the most volcanically active period of their evolution, outgassing rates can far exceed loss.

As the prospects of observing further sub-Earth sized worlds increases with improvements in detection methods and platforms [4], it is important to determine the conditions that are most likely to lead to habitability for planets of this size. Here, we utilise a coupled 1-D atmospheric and solid-state thermochemical mantle model [5] to investigate the habitability of sub-Earth sized exoplanets with stagnant and mobile lid tectonic regimes over a period of 10 billion years.

Methodology: We investigate the effect changes in planetary radii, core mass fraction, viscosity, tectonic regime and initial thermal state have on surface habitability using parametrised one-dimensional models [4]. We use these to track interior thermochemical evolution and resultant atmospheric properties to determine if and when a planet's surface is habitable. Here we define a habitable surface as one where liquid water is stable.

Our models consider planetary radii of 0.2–1 Earth radii (R_E). For each planet size we examine 3 distinct core mass fractions, representative of the Moon (0.02), Earth (0.33) and Mercury (0.7). We employ a fully non-dimensionalised Arrhenius equation for the viscosity that is temperature and pressure dependent. Viscosities are 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 $1.2*10^{21}$ Pa s [5].

Heat loss from the interior is modelled under mobile and stagnant lid tectonic regimes [5]. For mobile lid regimes the heat loss from the mantle is treated as a surface heat loss. However, under a stagnant lid regime, an immobile conductive lid forms reducing the convective potential of the mantle. Thus in a stagnant lid regime, the heat lost from the mantle is not directly equivalent to heat loss at the surface, but can be directly calculated from the thermal gradient of the conductive lid.

We initialize our models with a mantle temperature calibrated to the mid-mantle such that the initial mid-mantle temperature is within ± 100 K of the solidus. Accordingly, our models begin in a solid-state convective regime at the start of the simulation. We allow core temperatures to vary between adiabatic to super-adiabatic (up to 1250 K above the mantle temperature).

Solidus and liquidus temperatures are estimated using the water corrected parameterization of [6]. Importantly, melt evolution is linked to outgassing via a pressure and oxygen fugacity dependent gas speciation model [7]. We also assume the mantle has an Earth-like bulk silicate composition and is underlain by an iron rich core.

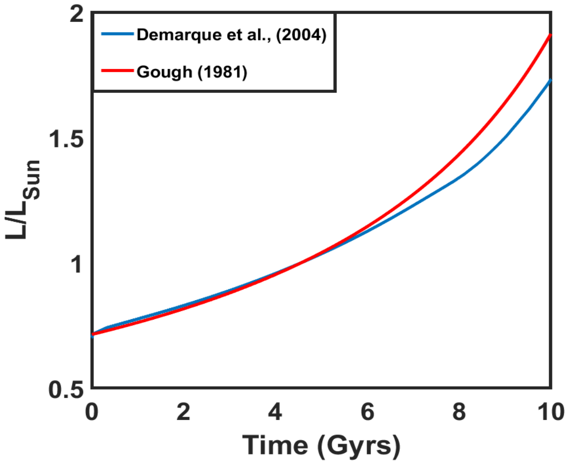

Figure 1: Comparison of the estimated relative luminosities of the sun through time [8] and the Yonsei-Yale evolutionary tracks [9]. Models deviate significantly when time is greater than the current age of the sun.

The planet’s surface temperature is determined, in part, by the greenhouse effect of CO_2 and H_2O as well as the change in equilibrium temperature caused by variable solar irradiance through time. We use the Yonsei-Yale evolutionary tracks for a Sun-like star [9] to model the evolution of stellar luminosity and the effect this has on planetary surface temperatures (Figure 1).

Results: The influence of tectonic regime on the outgassing rate of exoplanets is strongly correlated with planetary radii (Figure 2). Models with stagnant lid regimes attain nominal habitability faster than those with mobile lid tectonic regimes when the radius is below 0.8 R_E. As radius increases, mobile lid regimes begin to outgas more efficiently in the first half billion years of the models run time but thereafter, melt productivity declines rapidly.

However, the stagnant lid regimes for sub-Earth planets gradually release volcanic gases over time and eventually outpace mobile lid regimes. Peak outgassing productivity for stagnant lid regimes is attained between 0.4 and 0.6 R_E. The greater volume of melt produced by mobile lid regimes in the first few hundred million years and stagnant lid regimes later has also been observed in 2-D and 3-D models of the Martian mantle [10]. As radius increases further the productivity of stagnant lids declines rapidly, whereas the total volume of gases emitted in mobile lid regimes continues to grow. For planets with an Earth-like radius, mobile lid regimes always outpace their stagnant lid counterparts.

Conclusion: We find that the length of the habitable window for sub-Earth sized exoplanets can be maximised with a planetary radius between 0.4 and 0.6 Earth radii, an Earth-like core and a stagnant lid tectonic regime. The planetary bodies of this size, composition and tectonic regime can generate an atmosphere sufficiently thick to warm the planet and allow water to be stable at the surface, for an atmosphere generated exclusively by mantle degassing.

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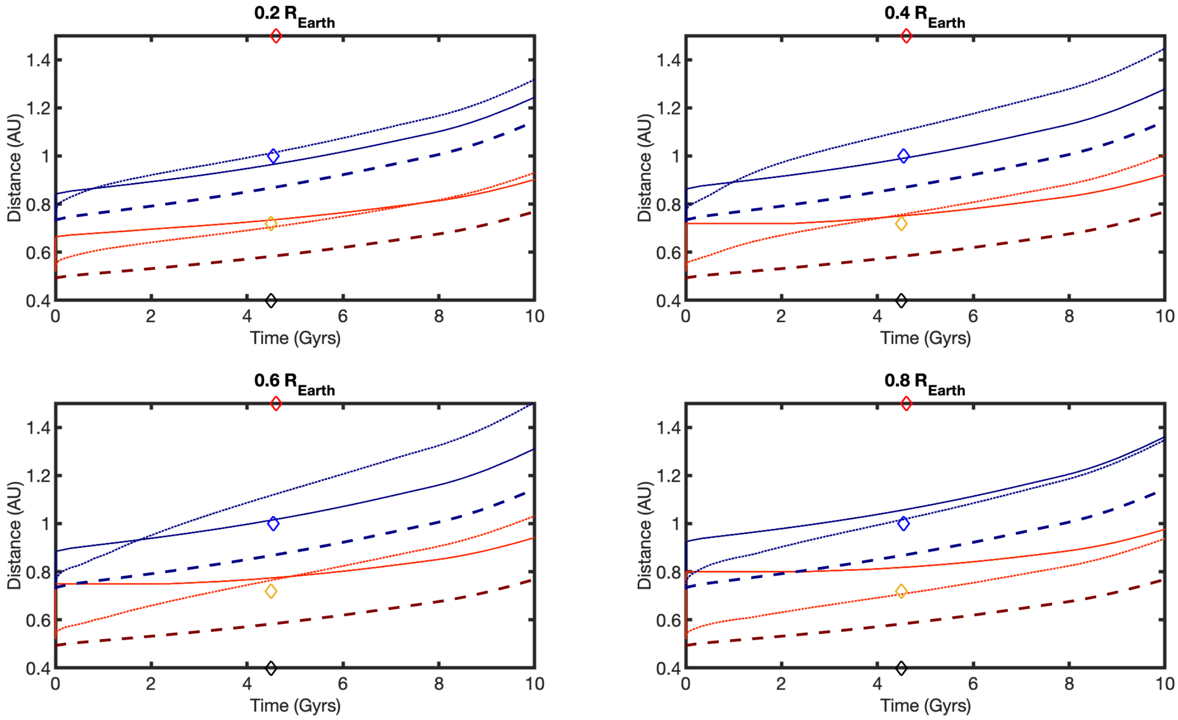

Figure 2: The habitable zone for sub-Earth sized planets. The models show that stagnant lid regimes are more efficient out-gassers when planetary radius is small. Line style denotes the tectonic regime (mobile – solid) (stagnant – dotted). Dashed lines represent equilibrium temperatures [9]. Colour denotes surface temperature (273 – blue) (323 – red). Diamonds show the location of terrestrial planets.