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Water-rich planets: how habitable is a water layer deeper than on Earth?

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Abstract

We study plausible constraints for the habitability of water-rich exoplanets and introduce a new habitability classification to be applied to water-rich planets from about Mars-size to almost Neptune-size planets with a deep water-ice layer.

1. Introduction

Water is necessary for the origin and survival of life as we know it. In the search for habitable worlds, water-rich planets therefore seem obvious candidates. The water layer on such planets could be hundreds of kilometers deep. Depending on the temperature profile and the pressure gradient, it is likely that at great depths a significant part of the water layer is solid high pressure ice. Whether the solid ice layer extends to the bottom of the water layer depends also on the thermal state of the planet. In this study we assess the depth of the liquid water layer as a function of the planet's mass, iron fraction and thermal state and determine the conditions for the ice layer to melt from beneath.

2. Model

A new ocean model has been developed including an interior structure model to infer the depth-dependent thermodynamic properties of high-pressure water and the possible formation of high-pressure ice [1]. In this study, we only consider pure water and neglect liquidus temperature depressing species like salts or ammonia. To determine the temperature profile in the water layer (where water is either liquid or in a high-pressure ice phase), we also need to know the heat flux out of the silicate mantle into the water layer. We therefore use a 1D parametrized model of the thermal evolution of core, silicate mantle and water layer, for either stagnant lid planets or plate tectonics mantles.

3. Results

3.1 Maximal ocean depth

Fig. 1 shows the maximal ocean depth and corresponding water weight fraction for varying planetary iron content or surface temperature as a function of planet mass.

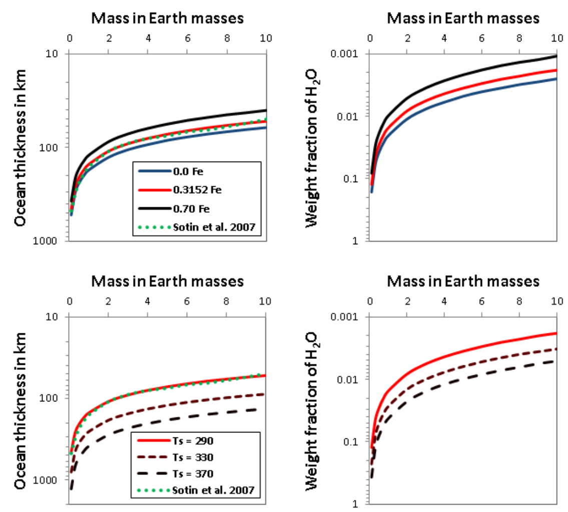

Figure 1: Maximal ocean depths and corresponding water weight fractions depending on iron content (top row) and surface temperature (bottom row) over planet mass. The green dotted line corresponds to the data published in [2] for an Earth-like composition and surface temperature. From [1]

We find that: 1) the depth of the liquid ocean increases with surface temperature, 2) an increasing planet mass reduces the maximum liquid ocean size due to the larger pressure gradient, and 3) a smaller iron content and thus average density of a planet (i.e. a larger planet radius for a fixed mass) slightly increases the depth of the liquid water layer.

3.2 Melting of high-pressure ice

Our results show that heat flowing out of the silicate mantle can melt an ice layer from below (maybe episodically), depending amongst others on the thickness of the ocean-ice shell and the mass of the planet, see Fig. 2. For thin ice layers, a steady lower ocean evolves. For increasing ice layer thicknesses, melting events become episodic, with fewer melting episodes for thicker ice shells.

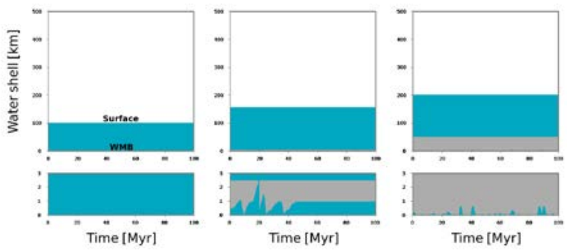

Figure 2: Thermal evolution of the water layer for a planet of one Earth mass with a surface temperature of 290K and water-ice layer thicknesses of 100km, 155 km and 200 km. The lower row shows the lowermost 3km of the water-ice layer. From [1]

3.3 Volcanism

Here we investigate how the planet mass influences the critical water/ice layer depth that would lead to a cessation of volcanism on stagnant lid planets and plate tectonics planets. We investigate the thermal evolution of the silicate mantle for varying water-mantle boundary (WMB) pressure and use upper mantle temperatures of either 2000 K or 2200 K.

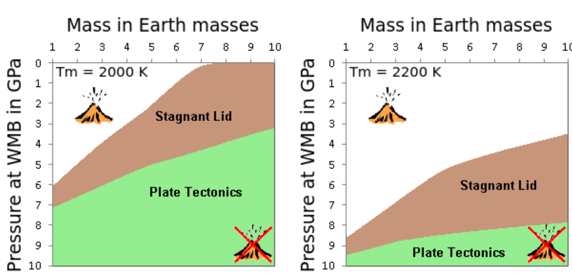

Figure 3: Example ocean depths, at which the WMB lithospheric pressure leads to cessation of volcanism. Brown regions show the area where no volcanism is expected for stagnant lid planets, and green for plate tectonics planets. From [1]

Fig. 3 shows that deep water-ice layers may hinder the existence of volcanism at the WMB due to the high WMB pressure for both stagnant lid and plate tectonics silicate shells. For the latter, volcanism is still possible for larger pressures than for stagnant-lid planets, since the warm mantle upwellings reach shallower depths. For even larger pressures, melt becomes denser than solids, and no volcanism is expected.

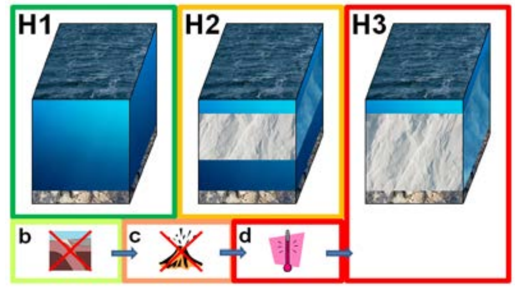

Figure 4: Our proposed new habitability classification for water-rich planets including subclasses (b-d), which consecutively reduce the habitability of classes H1 and H2. From [1]

4. Summary and Conclusions

Following the new habitability classification (Fig. 4), water-rich planets with a deep ocean, a large planet mass, a high average density or a low surface temperature are less habitable than a planet with an Earth-like ocean and might not be suitable candidates for the origin of life.

Acknowledgements

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