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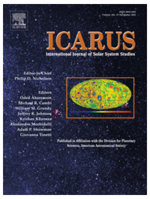

# Water-rich planets: How habitable is a water layer deeper than on Earth?

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ABSTRACT

Water is necessary for the origin and survival of life as we know it. In the search for life-friendly worlds, water-rich planets therefore are obvious candidates and have attracted increasing attention in recent years. The surface $H_2O$ layer on such planets (containing a liquid water ocean and possibly high-pressure ice below a specific depth) could potentially be hundreds of kilometres deep depending on the water content and the evolution of the proto-atmosphere.

We study possible constraints for the habitability of deep water layers and introduce a new habitability classification relevant for water-rich planets (from Mars-size to super-Earth-size planets). A new ocean model has been developed that is coupled to a thermal evolution model of the mantle and core. Our interior structure model takes into account depth-dependent thermodynamic properties and the possible formation of high-pressure ice.

We find that heat flowing out of the silicate mantle can melt an ice layer from below (in some cases episodically), depending mainly on the thickness of the ocean-ice shell, the mass of the planet, the surface temperature and the interior parameters (e.g. radioactive mantle heat sources). The high pressure at the bottom of deep water–ice layers could also impede volcanism at the water–mantle boundary for both stagnant lid and plate tectonics silicate shells.

We conclude that water-rich planets with a deep ocean, a large planet mass, a high average density or a low surface temperature are likely less habitable than planets with an Earth-like ocean.

## 1. Introduction

In the conventional view a habitable planet suitable for life as we know it requires the presence of liquid water. Therefore, environments that could support liquid water are at the forefront of the search for life beyond the solar system (e.g. Lammer et al., 2009).

### 1.1. Exoplanets and atmosphere evolution

The search for habitable planets has mainly focused on Earth-like exoplanets up to 10 Earth masses, the so-called super-Earths (Valencia et al., 2006). The large number and huge diversity of exoplanets in terms of orbital location, mass and likely composition, have strengthened efforts to understand planetary habitability. Several studies have concentrated on investigating planets already detected (e.g. Wagner et al., 2012; Wordsworth et al., 2010; Kaltenegger et al., 2011; Hu and Ding, 2011), others on analysing general aspects of habitability of super-Earths, especially on the existence of plate tectonics (e.g. Valencia et al., 2007; O'Neill and Lenardic, 2007; Elkins-Tanton and Seager, 2008; van Heck and Tackley, 2011; Stamenkovic et al., 2012; Stein et al., 2013; Noack and Breuer, 2014). Hydrogen-dominated mini-Neptune planets and water-rich planets also attracted increasing attention in the last decade (e.g. Kuchner, 2003; Leger et al., 2004; Sotin et al., 2007; Grasset et al., 2009; Fu et al., 2010; Spiegel et al., 2013; Lammer et al., 2014; Alibert, 2014; Rogers, 2015), especially since the first

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exoplanets with low density have been discovered in the recent years (Carter et al., 2012; Charbonneau et al., 2009; Gautier et al., 2012; Lissauer et al., 2013).

The protoplanetary growth-time, the average planetary density, and the host star radiation environment set the initial conditions for planets (Lammer et al., 2014; Stökl et al., 2015), which might evolve to habitable worlds with the right surface conditions. From observations of low mass exoplanets (Rogers, 2015) and derived average densities as well as theoretical studies (Johnstone et al., 2015; Lammer et al., 2014; Luger et al., 2015) indicate that exoplanets inside the habitable zones of low mass stars (M, K and G-type) should have masses between about 0.8–1.2 Earth-masses that they can lose sufficiently enough captured nebular gas (i.e., $H_2$, He, etc.) to become habitable. Depending on physical and chemical conditions in the protoplanetary disk, the amount of captured hydrogen from the protoplanetary nebula to the growing protoplanet and the efficiency of the host stars X-ray and extreme ultraviolet flux of a planets young host star the before mentioned studies indicate that especially super-Earths could be surrounded by dense hydrogen envelopes not lost during their lifetime. Terrestrial planets which originate after the protoplanetary nebula evaporated or which could lose their previous captured nebula gas will outgas their volatiles during the solidification of magma oceans (Elkins-Tanton, 2012; Lebrun et al., 2013). These outgassed atmospheres contain water in steam form that can condense and produce oceans when the planet orbits within the habitable zone.

### 1.2. Deep water layers and high-pressure ice

These planets can contain large amounts of water (we refer to 'water' as either liquid water oceans or water–ice shells), leading to water layers hundreds to thousands of kilometres deep (Grasset et al., 2009; Leger et al., 2004; Sotin et al., 2007) if they orbit inside the corresponding habitable zone (Kopparapu et al., 2013a; 2013b; Pierrehumbert and Gaidos, 2011). Formation of high-pressure ice polymorphs in the water–ice layer would separate the ocean from the silicate crust and make the ocean less habitable. Habitability of deep liquid ocean requires the continuous and adequate supply of sufficient nutrients, which Maruyama et al. (2013) postulate is only possible in shallow oceans, and a direct contact between the liquid ocean and the silicate shell may be essential.

Ice may also form at the surface of the water layer depending on the surface temperature and pressure (the latter can be high for dense hydrogen envelopes, see Choukroun and Grasset, 2007). The water underneath the ice shell may still be habitable, but in our study we only consider water shells for which the detection of biosignatures would theoretically be possible remotely. An ice shell might inhibit the direct interaction of life with the atmosphere (apart from influences from jets as observed for Enceladus or extracted surface material as suggested for Europa). We therefore only consider configurations where the surface is not covered by an ice layer and surface temperature is below the non-contaminated water vaporising temperature (for an Earth-like atmospheric surface pressure around 373 K). It should be noted that a water runaway greenhouse effect, as it was postulated for early Venus (Kasting, 1988), could start at temperatures even below 373 K depending on the composition and thickness of the atmosphere. Complete evaporation of several hundreds of kilometres of ocean is however a very time-consuming process and could take much longer than the time needed for the emergence of life.

For life a suitable temperature can be considered to be between the freezing point of water and the upper temperature limits for life as we know it, which is ~400 K (Corkrey et al., 2014; Holden and Daniel, 2004). Unlike temperature, an upper limit for pressure that allows for life to exist is not known. On Earth, living organism have been found at depths where the pressure exceeds several gigapascal (Picard and Daniel, 2013; Sharma et al., 2002).

Since liquid water is a prerequisite for life as we know it, water worlds can also be considered as suitable places for the origin and evolution of life at a first glance.

### 1.3. Origin of life on water-rich planets

The search for habitable planets is ultimately motivated by the search for life outside Earth. Habitability is defined as the ability to sustain life. But as has been argued before (Lammer et al., 2009), sustaining life is only one part of the game. When considering possible life outside Earth, it is important to consider not only the ability of a planet to sustain life, but also its ability to bring forth life. Even though it is not entirely clear how exactly life emerged on Earth, we know that in addition to the water from "classic" definitions of habitability, (Earth-like) life will also need access to three other things. These are (I) nutrients/building blocks of life; (II) catalitically active surfaces; and (III) an energy source. The building blocks of life (reduced organic carbon compounds) can either be produced by life itself, if and when sufficient simple nutrients are available, or be delivered as external food. This external delivery to the surface of a planet can be from either extraplanetary sources like comets, meteorites or interstellar dust particles, or it can be the result of abiotic chemical processes in the atmosphere of the planet like in Miller–Urey type reactions (Miller, 1953), or through photodissociation chemistry that is known to produce complex organic molecules (e.g. tholins like in Titan's (Khare et al., 1986) or Pluto's (Summers et al., 2015) high atmosphere). Simple nutrients, catalytic surfaces and harnessable chemical energy are all provided at the water–mantle boundary (WMB). The mineral surface at the WMB also provides a means of retaining molecules and reaction intermediates long enough for further reactions to take place in the extremely diluted ocean. It thus acts like a sponge for (organic) chemical compounds (Feuillie et al., 2013).

One theory for the origin of life on Earth is that it originated around hydrothermal vents on early Earth's ocean floor (Martin et al., 2008; Martin and Russell, 2007). The vents provide hydrogen ($H_2$) that, when mixed with carbon dioxide ($CO_2$) dissolved in the ocean water, is a very favourable starting point for reactions catalysed by mineral surfaces. These can make energy available for both metabolism and growth of organisms by carbon fixation. This theory is called autotrophic origin of life (Wächtershäuser, 1988). Another theory, called heterotrophic origin of life (Lazcano and Miller, 1999), states that early life did not produce its own food but was dependent on reduced organic carbon delivered from outside. According to this theory, the first proto-organisms likely formed by association of organic molecules into little bubbles called micelles (Luisi and Varela, 1989). Heterotrophic life forms feed on reduced organic material, which constantly needs to be delivered to the planetary surface (de Duve, 1991).

The availability of this reduced carbon for organisms living on an ocean planet depends on the layering of the ocean. With an ice layer blocking convection between the surface and a second, lower ocean at the WMB, heterotrophic origin of life at the WMB would be next to impossible (even though convective material transport through the ice layer may be possible on long time scales depending on the strain rate following Fu et al., 2010). Emergence of life atop an ice layer forming in the middle of the water shell would likewise be impossible, since the mineral surfaces at the WMB needed for retaining and concentrating material would be unavailable. In the case of autotrophic life the ocean would need both $CO_2$ and $H_2$ dissolved in it, so global access to both atmosphere and hydrothermal vents would be advantageous.