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Geophysical Limitations on the Habitable Zone

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Abstract

Planets are typically classified as potentially life-bearing planets (i.e. habitable planets) if they are rocky planets and if a liquid (e.g. water) could exist at the surface. The latter depends on several factors, like for example the amount of available solar energy, greenhouse effects in the atmosphere and an efficient CO_2-cycle. However, the definition of the habitable zone should be updated to include possible geophysical constraints, that could potentially influence the CO_2-cycle. Planets like Mars without plate tectonics and no or only limited volcanic events can only be considered to be habitable at the inner boundary of the habitable zone, since the greenhouse effect needed to ensure liquid surface water farther away from the sun is strongly reduced. We investigate how these geophysical processes depend on the mass and interior structure of terrestrial planets. We find that plate tectonics, if it occurs, always leads to sufficient volcanic outgassing and therefore greenhouse effect needed for the outer boundary of the habitable zone (several tens of bar CO_2). One-plate planets, however, may suffer strong volcanic limitations if their mass and/or iron content exceeds a critical value, reducing their possible surface habitability.

1. Introduction

The well-known circumstellar habitable zone (HZ) gives the distance to a star where liquid water may exist for a terrestrial planet. It assumes a fixed Earth-like CO2-cycle including the life-enhanced carbon-silicate cycle, active volcanism and plate tectonics, which are needed to regulate the atmosphere via the amount of outgassed greenhouse gases or subducted carbonates. The concept of the HZ, however, neglects the possible planetary diversity that we can already see in the Solar System. The Earth is only one out of three planets in the HZ - with Mars and Venus at the boundaries. Both those planets lack plate tectonics, a global magnetic field and (at least in the case of Mars) active volcanism. The planet mass as well as the interior structure can set constraints on the occurrence of plate tectonics and outgassing, and therefore affect the habitable zone.

2. Geophysical modeling

In order to understand how the interior of a planet may influence its potential surface habitability, we apply two numerical convection codes – CHIC [1] and GAIA [2]. We investigate how the mass and interior structure of terrestrial planets may influence the outgassing efficiency as well as the likelihood to form long-term plate tectonics.

We use an interior structure model (included in CHIC) to obtain profiles for the depth-dependent pressure and gravity acceleration. The density, the thermal expansion coefficient and the heat capacity at local conditions are obtained from equations of states of the relevant materials [1]. For the simulation of plate tectonics, a 2D convection code is used to investigate local stresses. Plastic deformation occurs if these stresses exceed the local, material-dependent yield stress. For the volcanic outgassing, we model the formation of partial melt in the mantle both with a 1D parameterized model (CHIC) as well as with 2D convection simulations (both codes).

3. Results

3.1 Plate tectonics depending on interior

Plate tectonics has an important influence on partial melting and thus volcanism since the melting temperature depends on the pressure. Upwelling of hot mantle material to the surface (e.g., at mid-ocean ridges) leads to large amount of melting and outgassing [3].

First, we investigate the possible initiation of plate tectonics for Earth-sized planets of different masses and thus compositions. We find that plate tectonics is less likely to occur for planets with a small core or a very large, Mercury-like core [3]. In the intermediate regime (with cores slightly larger than Earth's core), a long-wavelength convection structure occurs, that leads to larger stresses at the bottom of the lithosphere and enhanced plastic deformation.

Besides the core size, the mass of the planet also plays a crucial role for initiation of plate tectonics. For small bodies as Mars, our simulations suggest that long-term plate tectonics is unlikely without large tidal heating effects or unrealistic high amounts of radioactive heating, even though very short term lithosphere mobilization in the beginning of the thermal evolution cannot entirely be ruled out. Large super-Earths on the other hand may experience the opposite problem: too strong convection or too high radioactive heating can favor stagnant lid convection over plate tectonics, whereas cooler super-Earths may form an almost stagnant lower mantle due to the effect pressure has on the viscosity [4].

3.4 Outgassing depending on interior

For stagnant lid planets, outgassing is strongly limited if the pressure in the upper-most part of the mantle is large enough such that the melting temperatures are above the adiabatic mantle temperature. These large pressures can occur for either large iron cores (since iron is denser than silicates, influencing the surface gravity and thus pressure [3]), or for high planet masses, as shown in Figure 1 (using the 2D convection code GAIA). Note that if plate tectonics occurs, hot mantle material can reach the surface, leading to pressure-release melting.

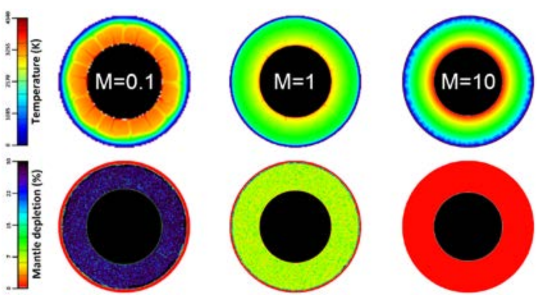

Figure 1: Temperature field and melt depletion after 4.5 Gyr for an Earth-like interior structure but different planet masses (neglecting possible plate tectonics) or mass and interior structure (right).

We use a 1D parameterized model (CHIC, [1]) to investigate how melting depends on both planet mass and interior structure, see Figure 2. We observe that the depletion of the mantle and thus the outgassing efficiency is strongly reduced for increasing planet mass (with zero outgassing from a critical mass and critical interior structure on). Depletion is also strongly reduced for increasing iron content and thus core sizes.

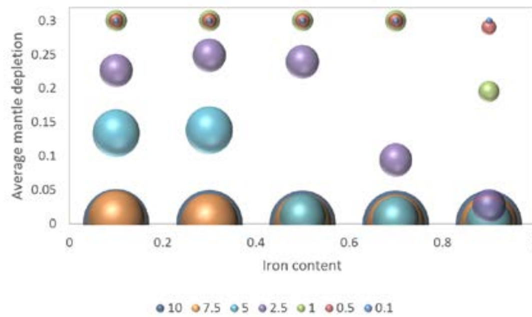

Figure 2: Average mantle depletion depending mass and iron content (i.e. iron core size).

Note, that the critical mass and iron content, from which on no depletion can be observed anymore, depends strongly on the initial mantle temperature. The amount of radioactive heat sources as well as a possible heat source enrichment in the (possibly primordial) crust could also influence the observed critical values.

4. Summary and Conclusions

The existence of a dense-enough CO_2 atmosphere allowing for the carbon-silicate cycle and release of carbon at the outer boundary of the habitable zone may be strongly limited for planets: 1) without plate tectonics, 2) with a large planet mass, and/or 3) a high iron content.

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