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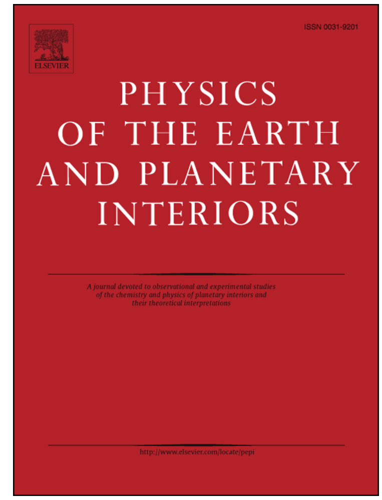

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Volcanism and outgassing of stagnant-lid planets: Implications for the habitable zone

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Abstract

Rocky exoplanets are typically classified as potentially habitable planets, if liquid water exists at the surface. The latter depends on several factors like the abundance of water but also on the amount of available solar energy and greenhouse gases in the atmosphere for a sufficiently long time for life to evolve. The range of distances to the star, where surface water might exist, is called the habitable zone. Here we study the effect of the planet interior of stagnant-lid planets on the formation of a secondary atmosphere through outgassing that would be needed to preserve surface water.

We find that volcanic activity and associated outgassing in one-plate planets is strongly reduced after the magma ocean outgassing phase for Earth-like mantle compositions, if their mass and/or core-mass fraction exceeds a critical value. As a consequence, the effective outer boundary of the habitable zone is then closer to the host star than suggested by the classical habitable zone definition, setting an important restriction to the possible surface habitability of massive rocky exoplanets, assuming that they did not keep a substantial amount of their primary atmosphere and that they are not in the plate tectonics regime.

Keywords: Exoplanets, habitable zone, melting, pressure, atmosphere

1. Introduction

In the search for habitable planets outside of the solar system, that means planets where life could evolve and flourish, the focus typically lies on rocky planets, where water could exist at the surface. The circumstellar zone around a host star, where liquid surface water could exist, is defined as the habitable zone (HZ, Hart, 1979; Walker et al., 1981; Kasting et al., 1993; Franck et al., 2000; Rushby et al., 2013; Selsis et al., 2007; Kopparapu et al., 2013b). Several studies investigated the width of the habitable zone, assuming the existence of an Earth-like CO_2-cycle including the life-enhanced carbon-silicate cycle, as well as active volcanism able to regulate the atmosphere via the amount of outgassed greenhouse gases or bound carbonates.

An inefficient outgassing at the outer boundary of the classical habitable zone reduces the surface temperature with respect to the classical HZ, thereby limiting the occurrence of water and reducing the width of the HZ (Noack et al., 2014; Kadoya and Tajika, 2014; Abbot, 2016). Here we discuss possible limitations of the HZ classification by studying constraints from the interior on the outgassing efficiency and hence the atmospheric surface pressure.

The Earth is only one out of three planets in the HZ of the Solar System - with Mars and Venus at the boundaries. Both planets lack active plate tectonics, a global magnetic field and (at least in the case of Mars) active volcanism. Planets like Mars without plate tectonics (except for possible early plate tectonics, Sautter et al., 2015) and no or only limited volcanic events (and thus limited outgassing potential of greenhouse gases) are not able to build-up a dense CO_2 atmosphere (limited to few bar CO_2, Grott et al., 2011). At the outer boundary of the HZ, the greenhouse effect would not be strong enough to ensure liquid surface water and the planets may not be considered as habitable at their surface. Venus, lying at the inner boundary of the HZ (depending on the HZ model, see for example Kopparapu et al., 2013b), has a dense CO_2 atmosphere and is not habitable. If the planet were to be at the outer boundary of the habitable zone or if some of the CO_2 from the atmosphere would have been extracted by weathering and carbonate formation, Venus might have been a habitable planet (at least in its past, see Way et al., 2016). At its orbit and with the current solar flux, Venus cannot have any liquid water at the surface. The early evolution of the planet, on the other hand, is still debated and varies between a runaway-greenhouse state and an Earth-resembling planet with surface water and possibly even plate tectonics.

Noack et al. (2014) have found that for terrestrial planets with the size of the Earth, the planet composition and therefore the interior structure can set constraints on the occurrence of plate tectonics and outgassing, and therefore affects the HZ. Kite et al. (2009) have investigated the influence of planet mass on volcanism for stagnant-lid and plate tectonics planets using a parameterized model. They found that the melting rate normalized to planet mass is only weakly dependent on planet mass. The study did neither include the pressure-dependence of the viscosity nor the compressibility effect of melt, but speculates that for massive stagnant-lid planets (above 5 Earth masses) the compressibility effect could lead to a decoupling of melting (which can occur beneath the lithosphere) and degassing at the planet's surface. Kopparapu et al. (2014) have investigated the possible influence of planet mass on the boundaries of the HZ by taking into account the effect of the surface gravity on the climate model, showing that an increasing mass moves the