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Can the interior structure influence the habitability of a rocky planet?

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ABSTRACT

Motivation: The most likely places for finding life outside the Solar System are rocky planets, some of which may have surface conditions allowing for liquid water, one of the major prerequisites for life. Greenhouse gases, such as carbon dioxide (CO_2), play an important role for the surface temperature and, thus, the habitability of an extrasolar planet. The amount of greenhouse gases in the atmosphere is in part determined by their outgassing from the interior.

Method: We use a two-dimensional convection model to calculate partial melting and the amount of CO_2 outgassed for Earth-sized stagnant-lid planets. By varying the planetary mass, we investigate the evolution of a secondary atmosphere dependent on the interior structure (different ratio of planetary to core radius). We further study the likelihood for plate tectonics depending on the interior structure and investigate the influence of plate tectonics on outgassing.

Results: We find that for stagnant-lid planets the relative size of the iron core has a large impact on the production of partial melt because a variation in the interior structure changes the pressure gradient and thereby the melting temperature of silicate rocks with depth. As a consequence, for planets with a large core (a radius of at least 70–75% of the planet's radius), outgassing from the interior is strongly reduced in comparison to a planet with the same radius but a small core. This finding suggests that the outer edge of the habitable zone of a star not only depends on the distance from the star and thus the solar influx but also is further limited by small outgassing for stagnant-lid planets with a high average density, indicating a high iron content (e.g. Mercury and the recently detected exoplanets Kepler-10b and CoRoT-7b). This contradicts previous models that have assumed CO_2 reservoirs being in principle unlimited for all planets. If plate tectonics is initiated, several tens of bars of CO_2 can be outgassed in a short period of time – even for planets with a large iron core – and the outer boundary of the habitable zone is not influenced by the interior structure. It is, however, more difficult for planets with a thin mantle (in our test case, with a thickness of 10% of the planet's radius) to initiate plate tectonics.

Our results indicate that the interior structure may strongly influence the amount of CO_2 in planetary atmospheres and, thereby, the habitability of rocky planets. To obtain better constraints on the interior structure accurate measurements of size and mass are necessary.

1. Introduction

Since the first detections in the early 1990s (Wolszczan and Frail, 1992; Mayor and Queloz, 1995), more than 800 extrasolar planets have been detected, and many candidates have been announced by the Kepler mission (Borucki et al., 2011). The increasing instrumental sensitivity allows for the detection of small, potentially rocky planets (see Fig. 1a). For some of these planets – for example, CoRoT-7b (Léger et al., 2009; Hatzes et al., 2011), Kepler-10b (Batalha et al., 2011), 55Cnc e (Fischer et al., 2008; Winn et al., 2011; Demory et al., 2011) and GJ 1214b (Charbonneau et al., 2009) – radius and mass measurements have been carried out, providing a mean density. Only for these planets can it be inferred whether they are mainly rocky or hold a substantial amount of atmosphere. Furthermore, if the mean density is known to be high enough, accuracy constraints on the internal structure of the planets can be derived (e.g. Valencia et al., 2006; Wagner et al., 2012). CoRoT-7b and Kepler-10b, for example, both have a high average density that suggests an iron core with the size of approximately 70% of the planet's size (Wagner et al., 2012). Note, however, that accurate measurements of radius and mass are necessary to assess possible interior structures of a detected exoplanet. Fig. 1b shows the possible range in the interior structure for an Earth-sized planet with one Earth mass but an inaccuracy of measurement of either 10% (dark shadowed regions)

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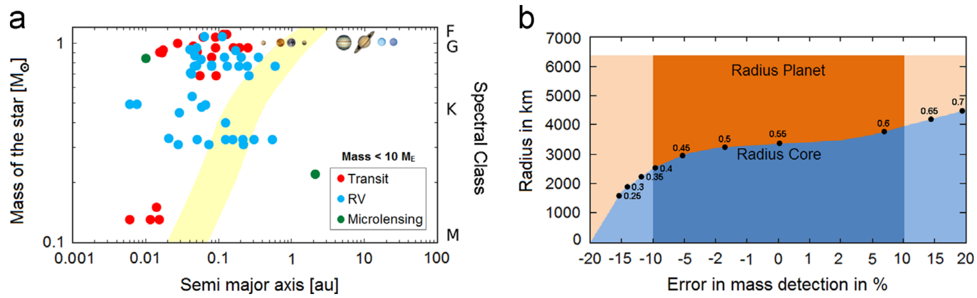

Fig. 1. Left: Detected potentially rocky exoplanets with less than 10 M_{Earth} in comparison with the Solar System. The planets are depicted over their semi-major axis and mass of their central star. The colour coding indicates the detection methods: cyan depicts planets found by radial velocity measurements (RV), red depicts planets detected with the transit method, and green depicts planets found by microlensing. Note that planetary masses from RV measurements are lower mass limits. The yellow area indicates the HZ in line with Selsis et al. (2007) and based on Kasting et al. (1993). Right: Possible interior structures and resulting radius ratios (black dots) for an Earth-sized planet with one Earth mass plus/minus 10% or 20% inaccuracies of measurement assuming Earth-like mantle and core compositions, after Rauer et al. (in review). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

or 20% (light shadowed region) considering Earth-like mantle and core compositions.

For rocky planets (usually assumed to have masses less than 10 M_{Earth}), one of the main scientific objectives is whether they are habitable, that is, hold an environment that can sustain life (Steele et al., 2006). The most important prerequisite for life is liquid water because all life on Earth needs liquid water at least for a part of its lifetime. This constraint has led to the typical definition of habitability on extrasolar planets requiring liquid water on the planetary surface, because it is difficult to observe subsurface conditions of these distant worlds and life on gas planets seems unlikely. From this, the so-called habitable zone (HZ) for rocky planets is defined, that is, the range of orbital distances over which liquid water may be possible on the surface (e.g. Hart, 1979; Kasting et al., 1993; Kopparapu et al., 2013). Several low mass planets (super-Earths to mini-Neptunes) and planetary candidates close to or within the HZ have already been detected: e.g. Gliese 581 c,d (Mayor et al., 2009; Udry et al., 2007), HD 85512 b (Pepe et al., 2011), GJ 667C c (Anglada-Escudé et al., 2012; Delfosse et al., 2013; Bonfils et al., 2013), HD 40307 g (Tuomi et al., 2013), and Kepler 22b (Borucki et al., 2012). However, for none of these planets could mass or radius be determined accurately enough to judge their bulk composition.

The possible existence of liquid water on a planetary surface depends on the surface temperature and the water reservoir in the planet. This water reservoir derives from planetary formation and the subsequent delivery of water by impacts. Because both processes are difficult to assess even for the planets in the Solar System, the habitability of extrasolar planets is usually determined by atmosphere models that evaluate surface temperatures assuming a water reservoir of one Earth ocean (e.g. Kasting et al., 1993). This, for example, has been done for the extrasolar planet candidate Gl 581d by several groups (Wordsworth et al., 2010, 2011; Kaltenegger et al., 2011; von Paris et al., 2010; Hu and Ding, 2011; Selsis et al., 2007), leading to constraints for atmospheric composition and mass for habitable surface conditions. This planet may be habitable for carbon dioxide (CO_2) partial pressures of the order of one to several bars, assuming that it is a rocky planet and holds a sufficiently large water reservoir. Thus, atmosphere modelling can help estimate if and for which atmospheric composition and mass an extrasolar planet could be habitable. However, whether these atmospheres are possible in terms of formation and evolution of planets has usually not been considered.

In addition to a primary atmosphere and the delivery of volatiles by impacts, the outgassing from the interior plays a major role in the buildup of an atmosphere. The outgassing of volatiles depends on the interior structure, composition and dynamics. On Earth, CO_2 is subject to the carbonate–silicate cycle, a negative feedback cycle that stabilizes the climate and the CO_2 content (e.g. Walker et al., 1981; Kasting et al., 1993). For Earth-like planetary atmospheres, CO_2 partial pressures have been estimated on the basis of a parameterization of this cycle (e.g. Edson et al., 2012; Abbot et al., 2012). Kite et al. (2009) apply a parameterized model calibrated to Earth to investigate mantle melting by varying both planetary masses and sizes. Modelling studies of rocky extrasolar planets have also estimated the primordial atmosphere on the basis of interior structure models (e.g. Elkins-Tanton and Seager, 2008b).

Interior models are often used to investigate how the interior dynamics can influence the surface of a planet, focussing, for example, on plate tectonics (Tackley, 1998; Trompert and Hansen, 1998), on the formation of the crust (e.g. Morschhauser et al., 2011) or on the crustal dichotomy of a planet (Keller and Tackley, 2009; O'Neill and Nimmo, 2010). However, atmospheric influences, such as the greenhouse effect, and resulting variations in surface temperature are often neglected. Some studies have concentrated on the buildup of the atmosphere (e.g. Grott et al., 2011b; Leblanc et al., 2012) and possible feedbacks on mantle dynamics using simple gray 1D atmosphere models (e.g. Phillips et al., 2001; Noack et al., 2012). The possible habitability of an Earth-like planet depends on the feedback between atmospheric processes and interior dynamics. In particular, plate tectonics, which depends on surface temperatures (e.g. Lenardic et al., 2008; Noack and Breuer, 2013), may have a strong influence on the evolution of the atmosphere.

Thus far, most of the numerical models treating interior dynamics (either 1D parameterized models or fully dynamical 2D and 3D models, which treat partial melting and volcanic outgassing self-consistently) have focused on the Solar System bodies, such as Mercury (e.g. Grott et al., 2011a), Venus (e.g. Armann and Tackley, 2012; Noack et al., 2012), the Earth (e.g. de Smet, 1999) and Mars (e.g. Morschhauser et al., 2011; Keller and Tackley, 2009; Sramek and Zhong, 2012). Numerical models for super-Earth planets have also been applied to investigate the effects of depth-dependent thermodynamic properties (Stamenkovic et al., 2012; Wagner et al., 2012), the propensity of plate tectonics (O'Neill and Lenardic, 2007; Valencia et al., 2007; Stein et al., 2011; van Heck and Tackley, 2011; Noack and Breuer, this issue) and the effects of variable surface temperature on the interior dynamics and its implications for the planet's volcanism (Gelman et al., 2011; van Summeren et al., 2011).

In this research, we employ a 2D interior dynamics model (Hüttig and Stemmer, 2008) to investigate whether the CO_2 outgassing rate of terrestrial planets depends on their interior structure, assuming that the planets comprise iron and silicates.

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