EPSC Abstracts
Vol. 12, EPSC2018-887, 2018
European Planetary Science Congress 2018

The controls of planetary bulk composition and tectonic style on the long-term evolution of outgassed atmospheres

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Abstract

Observations of super-Earth atmospheres have revealed information regarding the surface conditions of these exoplanets. More advanced instruments will allow future missions to observe atmospheres of exoplanets down to Earth size. Atmospheres of terrestrial planets form under interaction with their rocky interiors, by degassing from the magma ocean during the early life of the planet and by interaction with the solid rocky interior during the remainder of the planets life. Therefore, characterising an atmosphere and its composition based on observations may provide us with clues about the interior of a planet.

We have constructed a simplified model describing the simultaneous evolution of the planetary interior and its atmosphere. It is used to investigate possible evolutionary tracks of the atmosphere based on variations in planetary bulk composition, interior structure and tectonic setting, where only the end-members stagnant lid and plate tectonics are considered. Identifying separate tracks allows observations of planetary atmospheres to place first-order constraints on the planets interior.

1 Introduction

So far, the only properties that can be used to constrain interior conditions of Earth-sized planets are the planetary mass and radius, and the host star bulk composition. There is an ambiguity in investigating the interior based on the planetary mass and radius alone [1]. The bulk composition of the host star can be determined through stellar spectrography, and provides constraints on the bulk planetary composition in terms of heavier, rock-forming elements [2]. However, additional information is needed to accurately determine bulk planetary composition.

Since atmospheres form and develop in equilibrium with the rocky interior for terrestrial planets, atmospheric data provides more constraints on the interior composition and evolution. New technological developments will allow future instruments, such as the James Webb Space Telescope (JWST), to observe atmospheres of Earth-sized planets and provide these constraints. In this study, we link the bulk composition of planetary mantles in terms of Mg/Si and Fe/Mg to the coupled interior-atmospheric evolution in a parametrized model. We use this model to investigate whether the composition and interior evolution leave a measurable signature in the atmospheric size and composition.

2 Models

The model describes the coupled interior-atmospheric evolution of an Earth-like exoplanet around a Sun-like star in two phases: a primary phase during which a Magma Ocean (MO) crystallises and an atmosphere degasses, and a secondary phase, in which long-term processes govern the interaction between the solid rocky interior and the atmosphere. Model parameters involve both planetary composition and dynamic regime, which describes the interaction between the mantle and the surface. The planetary composition parameters are based on the host star bulk composition for the major rock-forming elements Fe, Mg and Si, where stellar bulk composition data is retreived from the Hypatia catalog [3]. The model only includes the most important greenhouse gases, H_2O and CO_2. In terms of dynamical regimes, we only consider stagnant lid and plate tectonics.

2.1 Primary evolution

During the first phase, the model describes bottom-up fractional crystallisation of a MO. The crystallisation sequence is determined based on thermodynamic data of the FeO-MgO-SiO_2 system at lower mantle conditions, published by Boukaré et al. [4]. The data shows that three stable phase fields are present at these conditions, crystallising ferropericlase (fp), bridgmanite (bm) and stishovite (st). At each step, the stable phase(s) given the current pressure and composition are determined and removed, after which the liquid composition is adjusted accordingly. Solubility of volatiles is also recalculated and volatiles are degassed accordingly.

The crystallising phases fp and bm are solid solutions between Mg- and Fe-end members, and both preferentially incorporate MgO over FeO. The remaining liquid MO becomes progressively more enriched in FeO, until the material crystallising at the top of the mantle has become so enriched that it becomes negatively buoyant. This development of the liquid MO composition is showsn in Figure 1, which shows the compositional pathway of the liquid MO for a range of compositions. At this point of the evolution, an overturn of the solid mantle occurs [5], where the compositional and density profiles of the mantle are inverted. We consider that subsequent mantle convection occurs across a single layer (whole mantle convection, blue dots in Figure 1), unless a threshold criterion (i.e., density difference of >200) is exceeded, and mantle convection collapses into two layers (red dots).

2.2 Secondary evolution

After the overturn is complete, the subsequent long-term evolution of the coupled interior-atmospheric planetary system can be modelled based on the degassed atmosphere and the properties of the solidified mantle. A 1D parametrized convection code based on Mixing Length Theory [6] is applied to model the thermal evolution of the mantle and the long-term in-/outgassing of the atmosphere. The tectonic regime and related mantle melting are considered to calculate volatile fluxes. In the stagnant lid regime, melt produced in the mantle is added to the crust, of which around 10% will reach the surface through extrusive volcanism and degas [7]. Volatiles preferentially partition into the melt, progressively moving volatiles from the mantle into the crust and atmosphere. In the plate tectonics regime, melting exclusively occurs at the very top of the mantle at plate boundaries. Complete degassing is assumed to occur here. In turn, regassing occurs at subduction zones. Since the goal is to use a simplified model, no atmospheric processes except for atmospheric escape are considered [8].

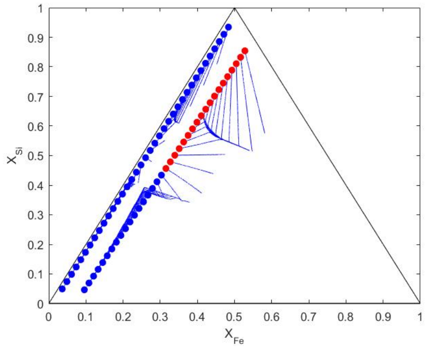

Figure 1: An overview of compositional pathways of the liquid MO during crystallisation, shown in the FeO-MgO-SiO2 triangle. The bulk compositions vary for molar MgO/(MgO+SiO_2) ratios between 0.05 and 0.95, and for FeO contents of 2 and 12 weight percent. Each starting composition has a coloured dot indicating the number of stable layers formed after overturn (blue: 1 layer; red: 2 layers).

3 Summary and Discussion

A simplified model describing the simultaneous evolution of a planetary interior and its atmosphere is constructed to study the way interior conditions affect the atmosphere. The goal was to find distinct atmospheric evolutionary tracts, so atmospheric observations can be used to constrain interior conditions. Since the three phases in the FeO-MgO-SiO_2 diagram that are stable throughout most of the mantle have different volatile solubilities, retaining varying amounts of volatiles in the solidified mantle. Since outgassing of H_2O is limited for high atmospheric pressures while outgassing of CO_2 is affected by atmospheric pressure to a much lesser extent [9], retention of volatiles in the liquid MO and solidified mantle affects the final H_2O/CO_2 ratio of the atmosphere.

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