Posters

Duration of magma ocean in the early Earth with a grey and a H2O steam atmosphere.

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1. Introduction

The early period of terrestrial planetary evolution likely included a phase where the mantle was molten to a large degree, known as magma ocean [7]. The energy needed for melting was made available to the system through delivery of impactors, release of potential energy in the interior during its differentiation and the decay of early radiogenic elements [2]. The system is estimated to have a low viscosity compared to water and convect vigorously. Our Moon is argued to have experienced such a phase, due to the buoyant plagioclase found close to its surface. However, we do not have constraints on the duration of this phase, neither on our planet nor its satellite.

A molten silicate mantle is expected to contribute to the building of a secondary atmosphere, due to extensive outgassing of volatiles from the interior. In this study we examine the cooling rate of the mantle that starts in magma ocean state, mediated by the presence of an atmosphere composed of greenhouse gases. We follow the system until the temperature of the mantle drops below the rheology front transition temperature, a value that depends on the composition of the mantle. We are studying the role of two volatiles in the atmosphere and we focus especially on the role of water. We find that a planet could even be trapped in a long-term magma ocean stage with the suitable combination of albedo and orbital distance.

The interior-atmospheric coupling helps us better constrain the Hadean period on our planet and the Moon, and gain insight for rocky exoplanets that could be found in similar stages, in the future.

2. Methods

We build a model based on [5], with differences in the interior and the atmospheric treatment, in order to calculate solidification times for indicative initial concentration of volatiles.

For the case of the steam only atmosphere we use a line by line model [6].

In order for the system to be in steady state, a balance between the convective flux at the top of the magma ocean and the net flux at the top of the atmosphere (hereafter mentioned as TOA) is demanded:

(1)

A solution to the suggested energy flux balance is found through iteration, with varying inputs: the viscosity of the melt, potential temperature of the mantle, and outgassed atmospheric gases. The surface temperature and the cooling flux are found at each iteration. With these, the energy equation is resolved and yields the thermal evolution of the system. Solubility curves are used to calculate the volatiles that are exsolved, assuming saturation conditions. The mantle starts from a global molten state at 4000 K, well above its phase change temperature and solidifies from the bottom to the top, due to the characteristic steeper slope of its adiabat compared to the melting curves. When the last layer reaches the rheology front temperature at the surface, the magma ocean phase ends.

3. Results

The configuration in equation (1) ensures cooling if both fluxes are positive. The convective cooling flux is always positive for a surface temperature that is lower than the temperature of the interior. The grey atmosphere of [1,2,5] is able to represent both and .It yields positive values for the range of volatiles assumed and ensures that the magma ocean phase has finite duration. In the colourmap of Fig.1 (left) we thus calculate the solidification times for various volatile contents. An Earth sized planet that contains an ocean of initial H_2O (300 bar) and CO_2 equivalent to the content in the crustal carbonates (100 bar) is marked as “reference”. The solidification time barely exceeds 5 Myr, even by assuming a very rich chondritic abundance of water (CC1%wt). However, in our results that employ the steam atmosphere, we find that the atmosphere can reach an outgoing radiation limit that allows the net flux to be either positive or negative at the TOA, according to the incoming energy from the Sun [4]. In Fig.1 (right) we see a set of limiting curves, each of which defines the distance for which a planet with given albedo can be trapped in the magma ocean stage, as it stops cooling. The shaded region corresponds to estimated values for a steam albedo without clouds taken from the literature [3]. Any albedo higher than the curve at a given distance ensures that the magma ocean phase will be transient for the system. Note, that this limit is different for an atmosphere that has a different mass of water steam, ranging from 4 bar to 300 bar. The highest the mass of the atmosphere, the more efficient is the absorption and the lowest the limit of radiation at the TOA that should be equilibrated by the solar irradiation. This effect pushes the transition limit of long-term to transient magma ocean, further away from the Sun, the more massive the outgassed steam atmosphere is. Future work is planned in order to include the effect of additional gas species on this mechanism.

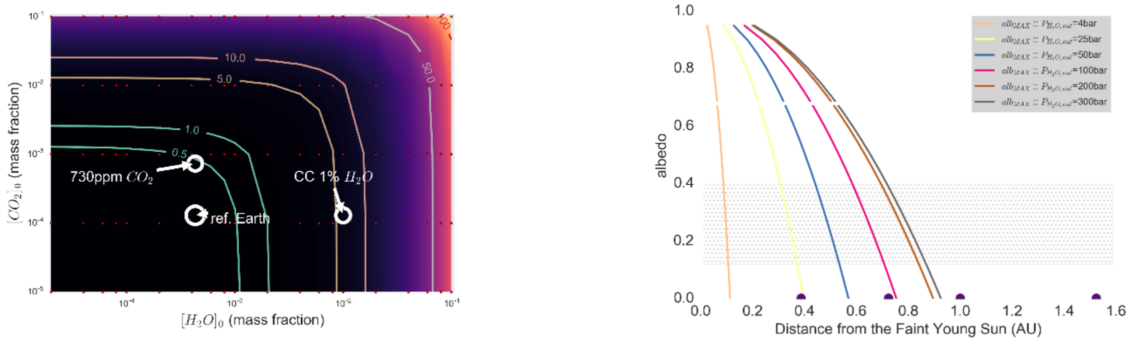

Figure 1: Left: The solidification time for a planet of Earth size (colormap) is plotted for different combinations of initial H_2O and CO_2 abundances in the mantle, as calculated with the use of grey approximation for the atmosphere, described in [1]. Right: The maximum albedo/ distance combinations for a planet of Earth size, with H_2O steam atmospheres that vary from 4 to 300 bar.

4. References

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Short Summary

The early evolution of terrestrial planets likely included a phase of extensive molten mantle accompanied by outgassing of a secondary atmosphere, referred to as magma ocean. We use a model to resolve its thermal evolution and put constraints on the role of steam water in thermal blanketing.