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Influence of initial CO_2 content on a planet surface conditions at the end of the magma ocean phase

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Abstract

The earliest compositional differentiation of the terrestrial planets, the formation of their outgassed atmospheres, and the existence of condensed water oceans over their solid mantles, are conditioned by magma ocean (MO) formation and solidification. Recent studies have suggested that depending on the planet initial water content and its orbital distance to the sun, two types of conditions, with (I) or without (II) water ocean, can prevail at the end of the MO phase. We use a coupled interior-atmosphere model of MO thermal evolution to go further and study systematically the influence of the planet initial CO_2 content on the resulting surface conditions (temperature, volatiles, condensed water) at the end of the MO phase. The position of the boundary between the two regimes is shown to depend also on the initial CO2 content.

1. Introduction

Conditions at the end of the magma ocean stage are important to constrain the subsequent evolution of a planet. Indeed, the resulting interior compositional structure constrains the geodynamical regime of a rocky planet and the resulting surface conditions determine the possibility of water condensation. Those conditions are therefore essential to determine the habitability of a planet and its temporal evolution.

Hamano & al. [1] demonstrated that the initial H_2O content of magma oceans has a significant influence on planetary evolution, leading to two different types of planetary surface condition as a function of the orbital distance from the sun. Here we decided to test specifically the influence of the initial CO_2 concentration on the surface condition at the end of the magma ocean phase.

2. Method

We used a 1-D parameterized convection model of a magma ocean coupled with a 1-D radiative-convective model of the atmosphere (Lebrun et al, 2013 [1]). The entire mantle of the planet is assumed to have melted, following collision with a giant impactor. The resulting MO is convecting at very high Rayleigh number and crystallizes from the bottom up. The magma viscosity depends on both temperature and crystal content. A rheological transition with a sharp increase in viscosity happens when the crystals volume fraction becomes greater than 60%. The end of the MO phase is defined as the time when this rheological front reaches the surface.

The 1-D radiative-convective atmospheric model (Marcq, 2012, [3]) considers an H_2O-CO_2 atmosphere which follows a vertical temperature profile similar to Kasting (1988) and Abe and Matsui (1988). Opacities in the thermal IR are computed using a k-correlated code (KSPECTRUM). The reflectance of the clouds of this non-gray model can be varied, as well as the orbital distance from the sun.

The MO interior and the atmosphere are coupled through the balance of the atmospheric heat flux at the surface with the convective heat flux out of the mantle. Furthermore, the atmospheric model takes into account the exsolved volatiles from the magma ocean as the cooling progresses, and the mass fraction of dissolved volatiles in the MO is assumed to be in equilibrium with the atmospheric volatile content at each time step, due to vigorous convective movements in the liquid MO.

3. Results

Figure 1 below shows, for a given initial H_2O concentration ($4{,}3.10^{-2}$Wt% ~ $2M_{\mathrm{EarthOcean}}$), the thermal evolution of the magma ocean for a type I planet at 1 AU (red curves) and for a type II planet at 0.63 AU (blue curves), without CO_2. The differences between the two types of planets appear clearly: whereas the solidification time of the type I planet is less than 1 Myr, the type II planet isn't cooled after ten Myr with a non-gray atmosphere. By varying the initial CO_2 content, we've seen that those times are only affected by 30% at most.

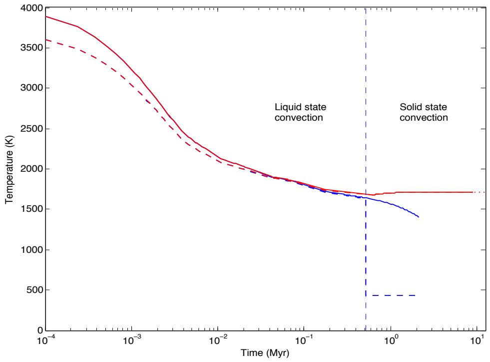

Figure 1: Evolution of the surface (dashed lines) and potential temperatures for type I (blue curves, 1.00 AU) and type II planets (red curves, 0.63 AU), with an initial water mass of twice the current oceans mass on Earth. These cases without CO_2 but a non-gray atmosphere compare well with Hamano et al's study.

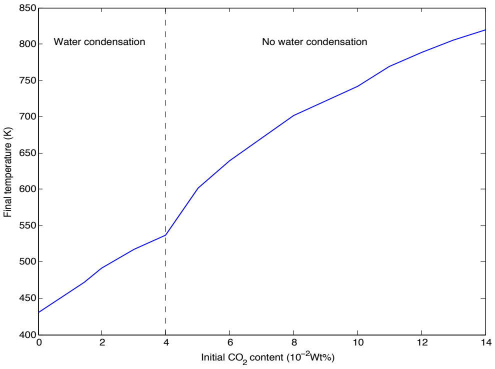

Figure 2: Surface temperature at the end of the magma ocean as a function of the initial CO_2 content for a solar distance of 1 AU, initial H_2O content equivalent to 0.6 current Earth's oceans, non-gray atmosphere.

Figure 2 shows the strong influence of the initial CO_2 content on the surface temperature obtained at the end of the magma ocean. It reveals the existence of two regimes, where the water condensation occurs or not and demonstrates that the initial CO_2 content of a planet must be taken into account to understand the evolution of a planet and especially its surface conditions. Thanks to those results, we can constrain the initial CO_2 content of a magma ocean for a given initial H_2O content for a planet where water condensed or not.

4. Conclusions

Using a combined atmosphere-MO evolution model, we showed that the initial CO_2 content significantly affects the surface conditions at the end of the magma ocean stage. For example, water condensation, depending on the surface temperature and pressure, can not occur above an initial CO_2 content of 4.10^{-2}wt% for a distance of 1 AU from the Sun with an initial H_2O content equivalent to 0.6 current Earth's oceans, in a non-gray atmosphere for an Earth-like planet. Thus, depending on the initial volatile content at the accretion time, it affects the habitability of a planet. However, this parameter doesn't affect significantly the solidification time of magma oceans. The model will also allow us to constrain the initial parameters that induce condensation such as the distance from the star and the initial CO_2 content for a given initial H_2O content. This model should be also applicable for exoplanets.

References

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