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The possibility of catastrophic magma ocean degassing and implications for the formation of early planetary atmospheres

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Abstract

The heat provided by accretion and differentiation is sufficient to melt the silicate mantle of a terrestrial planet or planetary embryo wholly or partially creating magma oceans that may span a wide range of depths. The solidification processes in these magma oceans create an important link between the properties of the solid mantle and the atmosphere: Depending on the ratio of volatiles retained in the mantle to the volatiles degassed to build the atmosphere, magma oceans with similar starting compositions may lead to planets with dry or wet mantles and substantial or minimal atmospheres. The build-up of an early atmosphere also sensitively affects the heat loss to space and thereby the solidification rate of the magma ocean

The goal of this study is to constrain which factors determine magma ocean degassing and thereby the growth of an early planetary atmosphere and volatile retention in the mantle. Our model is based on a detailed analysis of bubble nucleation, growth and breakup during magma ocean solidification. We find that degassing does not necessarily occur continuously as commonly assumed. Instead, we suggest three end-member types of degassing histories ranging from continuous to catastrophic and negligible degassing and discuss how these depend on planetary and magma ocean properties.

1. Introduction

An important uncertainty in current models for the early evolution of terrestrial planets is the origin and composition of primordial atmospheres. Three primary sources may contribute to planetary atmospheres: capture of nebular gases, early degassing during accretion, and late assimilation of volatiles from cometary impactors. While capture of nebular gases is thought to be critical for gas giants, the mass of terrestrial planets is probably too low to capture and retain nebular gases. Furthermore, nebular gases may have largely dissipated from the inner solar system by the time terrestrial planets have grown to their current sizes. Degassing during accretion is thus a reasonable starting point for modeling early planetary atmospheres on terrestrial-like planets and exoplanets.

Magma oceans are thought to have formed on a wide variety of planetary bodies ranging from small planetesimals [1] to Super Earths with 1-30 Earth's masses [2]. This variability in planetary properties raises the question which parameters determine the degassing history of a magma ocean and whether degassing necessarily occurs continuously as commonly assumed. The goal of this study is provide new insights into the importance of different parameters such as planetary mass, initial volatile content and depth of the magma ocean for magma ocean degassing and atmospheric growth based on an analysis of the bubble dynamics at microscopic scales.

2. Method

Our model of bubble dynamics consists of two components. As a first step, we analyze bubble nucleation, growth, and breakup at the microscopic scale in order to estimate when bubbles nucleate and what their size distribution is likely to be. Depending on whether nucleation occurs homogeneously or heterogeneously, significant supersaturations might be required for nucleation to occur. In the second step, we identify the implications of bubble dynamics at the microscopic scale for degassing at the planetary scale. Our analysis indicates that the presence of bubbles at shallow levels in the magma ocean will tend to cause a shift from thermal to buoyancy-driven convection within this depth range, at least as long as the solid fraction in suspension is sufficiently low and gravity sufficiently high.

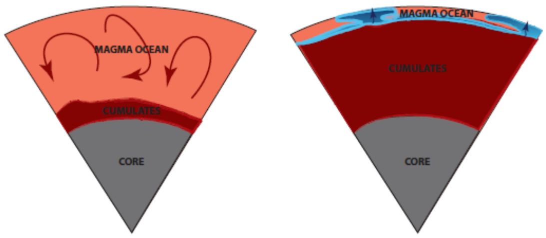

Fig. 1: Overview of the two phases of solidification of a magma ocean experiencing catastrophic degassing. Left: Nucleation is delayed by insufficient superaturation or entrainment of bubbles and volatiles do not degas. Right: Once bubbles have nucleated and reached a critical size and density required for degassing, compositional convection becomes dominant at shallow depths.

3. Results

Based on the dynamics of nucleation and entrainment, magma oceans may follow three distinct degassing paths: (1) continuous degassing, (2) catastrophic degassing, and (3) negligible degassing.

Continuous degassing is a viable scenario if nucleation requires negligible supersaturation or if the volatile content is high enough to initiate degassing immediately. A key factor facilitating high initial volatile contents is a preexisting atmosphere, because volatiles in the magma ocean equilibrate with those in the atmosphere. We hypothesize that continuous degassing is likely on Super Earths since very massive planets are more likely to have inherited an atmosphere from accreting protoplanets.

Catastrophic degassing is pertinent for planets of intermediate size and relatively low initial volatile contents. We hypothesize that magma oceans on the terrestrial planets in our solar system could have degassed discontinuously through a single (or possibly multiple) catastrophic degassing events. The solidification history of the magma ocean is divided into two distinct segments by catastrophic degassing (Fig. 1). Compared to discontinuous degassing, magma oceans that exhibit catastrophic degassing are characterized by a less substantial early atmosphere and a higher volatile content in the solidified mantle.

Negligible degassing in combination with volatile enrichment in the silicate mantle is a likely scenario for magma oceans on small planetesimals or very shallow magma oceans on larger planets. Although volatile enrichment increases rapidly during the very late stages of solidification, degassing is probably hampered by the rapidly increasing solid fraction in the solidifying mantle. The dynamic consequences of a lack of degassing are (1) high volatile contents in the solidified magma ocean, (2) a minimal atmosphere, and (3) exceptionally rapid time scales of solidification.

6. Summary and Conclusions

We present a new framework for modeling the degassing of magma oceans. Its main contribution as compared to previous approaches is that we consider bubble nucleation, growth, and breakup at the microscopic scale. Numerous parameters determine the degassing history of a magma ocean. The three most important parameters are the initial volatile content, the depth of the magma ocean, and the gravitational field. In terms of volatile content, carbon dioxide is of particular importance for facilitating nucleation. The insight that the magma ocean depth plays an important role points to one process by which terrestrial planets could begin with different internal volatile budgets.

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