The possibility of catastrophic degassing and implications for the formation of early atmospheres.

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Introduction

Partial or whole-planet magma oceans produced by oligarchic accretionary impacts provide a starting point for modeling planetary evolution. A crucial component in these models is the formation of an early atmosphere, which is related to understanding when volatiles begin to exsolve from the magma ocean and in what quantities.

Previous studies have recognized and studied the importance of early atmospheres [1, 2, 3, 4, 5]. We complement this earlier work by investigating the various stages of bubble formation, growth, and breakup and how they determine the degassing regime of the magma ocean. We find that the key parameter controlling the degassing history of early terrestrial planets and formation of their earliest atmosphere is the initial volatile content.

Terrestrial planets are thought to have accreted from planetesimals consisting of chondritic material. A wide spectrum of volatile concentrations have been reported for chondrites ranging from 20% [6] to minimal volatile contents [7]. Given this uncertainty, we explore the ramifications of a wide range of initial volatile contents.

We hypothesize that solidification of magma oceans is likely to proceed in two main stages: (1) Initially, volatile contents are in most cases insufficient to trigger massive bubble nucleation. At this stage degassing is not appreciable and solidification exceptionally rapid. (2) Once a critical super-saturation of volatiles is reached, widespread nucleation and bubble growth will create sufficient void fractions for compositional convection to dominate flow behavior. The combination of high supersaturations in the magmatic liquid and a shift in the mode of convection could lead to catastrophic degassing and a very rapid formation of a significant early atmosphere.

Nucleation model

We model bubble formation in the interior of the magma ocean based on the homogeneous nucleation theory pioneered by Volmer and Weber [8] and Becker and Döring [9]. The Gibbs free energy associated with formation of a single bubble is

$$\Delta G = 4\pi r^2 \gamma - \frac{4}{3}\pi r^3 (p - P) \qquad (1)$$

where r is the radius of the bubble, γ the surface tension, p the internal pressure in the bubble, and P the external, magmatic pressure. The height of the kinetic barrier,

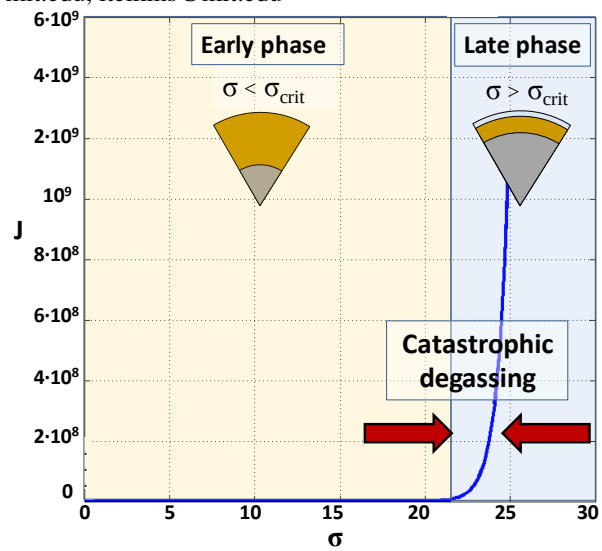

Figure 1: Dependence of the rate of homogenous nucleation of bubbles J on the supersaturation of the melt σ. Note that both quantities, the supersaturation σ and the nucleation rate J have been non-dimensionalized. In this plot, the range of catastrophic degassing lies at $20 \leq \sigma \leq 25$.

ΔG^*, has to be surmounted for a phase change to take place. Using the Arrhenius equation, we obtain an approximate expression for the rate of nucleation

$$J = C \exp\left(\frac{-\Delta G^*}{kT}\right) = C \exp\left(\frac{-16\pi\gamma^3}{3kT\sigma^2 P^2}\right) \qquad (2)$$

where J is the rate of nucleation, C is approximately taken to be a constant, k the Boltzmann constant, σ the supersaturation, and T the temperature [8, 9]. We note that C is material specific and not well constrained for silicic fluids. Figure 1 shows how the nucleation rate J scales with the supersaturation σ. It demonstrates that the nucleation rate J increases by several orders of magnitude over a limited interval of supersaturations σ.

We argue that nucleation outside of the critical interval highlighted by two arrows is negligible. It is important to note that the exact location of this critical interval of supersaturations depends on the composition of the magma and there is considerable uncertainty associated with estimating the critical supersaturation for magma oceans. However, the critical supersaturation is always

expected at $\sigma \gg 1$ for homogeneous nucleation.

Results

Fig. 1 also illustrates why the fate of the earliest atmospheres for terrestrial planets is determined primarily by their initial volatile content. If the initial volatile content is sufficient such that $\sigma > \sigma_{cr}$, bubble formation will initiate immediately after formation of the magma ocean. For the more likely case of low initial volatile contents, however, no appreciable nucleation is to be expected during early solidification. As a consequence, magma-ocean solidification will be exceptionally rapid during this early phase, because an insulating atmosphere is the primary rate-limiting factor in magma-ocean solidification [2]. Rapid interior cooling in turn makes the time to clement surface conditions rapid, preparing the planetary surface for liquid water [10]. As the liquid portion of the magma ocean is diminished, it will get enriched in volatiles continuously. Thus, even magma oceans with low initial volatile contents will eventually reach a point where the remaining liquid is highly supersaturated in volatiles.

Once the critical level of supersaturation $\sigma > \sigma_{cr}$ is reached, widespread nucleation is expected to occur. At the time of nucleation, gas bubbles are rarely larger than 1 μ m and typically even Brownian motion will be sufficient to keep them suspended in the magmatic flow as indicated by a small Péclet number (Pe < 1). Thus, growth through expansion and diffusion is required for the bubbles to be able to decouple from the flow and rise to the surface under their own buoyancy to degas.

Widespread nucleation and bubble growth increases the bubble fraction ϕ in the liquid magma notably. It is likely that even as long as individual bubbles remain small, the void fraction in the magma ϕ will be sufficient to cause a switch from thermally- to compositionally-driven convection. The relevant non-dimensional number capturing when this change in the mode of convection occurs is given by the ratio of thermal to compositional buoyancy force:

$$\Pi = \frac{\alpha \Delta T \rho}{\phi(\rho - \frac{P}{RT})} \tag{3}$$

where α is the thermal expansivity, ρ the density of the magma, and R the gas constant.

This shift in the driving force for convection determines the onset of catastrophic degassing, because once convection is driven by convection, bubbles in all sizes ranges will be swept up to the surface and degas rapidly to form the earliest atmosphere.

Discussion

Our models show that the solidification of magma oceans with low initial volatile content proceeds in two main stages: during its early stages, solidification is exceptionally rapid and not accompanied by formation of an early atmosphere. Instead, the earliest atmosphere will form suddenly and rapidly once the liquid magma ocean has reached a critical level of oversaturation. At this point, the driving force behind convection is likely to switch from thermal to compositional buoyancy, aiding the rapid build-up of an early atmosphere.

Our models indicate that the initial volatile concentration in a magma ocean is the key factor controlling how and when an early atmosphere is formed. If the volatile supersaturation is close to the critical value from the beginning, atmosphere formation will proceed gradually as assumed in previous models [2, 1, 5, 10]. For magma oceans with very low initial volatile content, atmosphere formation will be sudden and constitute an essentially catastrophic degassing event when the magma ocean is already largely solidified.

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