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Degassing chemistry variation on rocky exoplanets

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Abstract

Volcanic degassing from the interior of a rocky planet critically depends on the composition, available energy and mantle chemistry. We investigate more specifically how the interior redox state and the concentration of volatiles stored in the mantle after the accretion can affect the build-up of a secondary atmosphere; in particular, the resulting gas species and the mass of the atmosphere.

1. Introduction

One of the most promising developments in exoplanetary science is the planned spectroscopic characterization of rocky exoplanetary atmospheres with future telescopes (e.g., JWST, ARIEL, E-ELT) and mission concepts (LUVOIR, HabEx). These will spectroscopically determine key chemical species in the atmospheres of the nearest small exoplanets, enabling spectral retrieval of atmospheric pressure, temperature, and composition.

The atmosphere of a rocky planet is built in multiple stages. Generally, atmospheres can be accreted from the proto-planetary disk (primordial), outgassed during the cooling of a magma ocean (primary), or outgassed by volcanism during the long-term evolution of a planet (secondary). This final stage would eventually govern the planet's habitability.

Model studies of primary and secondary outgassing on super-Earths show that their efficiency depends on planetary bulk properties: mass, thermal state, age, and tectonic style, primarily; and secondarily, bulk composition [1-6]. [2, 4, 6] laid a foundation for how silicate melt volumes and associated volcanism may depend on astrophysical observables (e.g., planet mass), but holding to the assumption of a graphite-saturated, oxidized mantle. Here we investigate the role of the redox state on the outgassed atmospheric species and the atmosphere density.

2. Model description

Starting from the magma ocean degassing efficiency determined in [1], we assume different cases of volatile accretion and storage in the mantle after the magma ocean. Evolution scenarios for the interior are taken from [6] predicting the variability of volcanic activity for planets of masses between 1 and 8 Earth masses, with variable mantle composition, volatile and heat sources concentration, as well as other initial parameters. Water partitioning into melt is modeled depending on a partition coefficient (we use D_{H2O} = 0.01 [7]) and the local melt fraction. Carbonates dissolved in the melt are determined depending on the local redox state, temperature and pressure conditions [8]. When melt rises to the surface and recrystallizes (either as intrusive or extrusive volcanism), the actual gas speciation in the melt is calculated depending on the melt redox state, temperature and pressure using the equilibrium and mass-balance method [9, 10] as well as the gas solubility [11]. The variability of gas speciation in the C-O-H domain is depicted in Fig. 1.

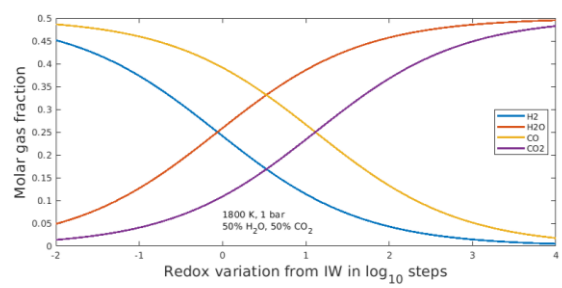

Figure 1: Molar fractions of degassed species with equal molar fraction of H_2O and CO_2 in the melt for different redox states from more reduced (-2) to more oxidized (+4) states with respect to the Iron-Wustite mineral buffer.

From the evolution scenarios, we calculate the total mass of outgassed molecules for H_2, H_2O, CO and CO_2. In the investigated redox and temperature range, amounts of O_2 and CH_4 are negligible small. From the mean molecular weight of the atmosphere (assuming here no erosion or other atmosphere sinks) we then determine the partial pressures of the different gas species as well as the thickness of the atmosphere following [12].

3. Summary and Conclusions

We confirm our previous results [4, 6] that the planet mass is one of the main factors influencing the thickness of the atmosphere (see Fig. 2).

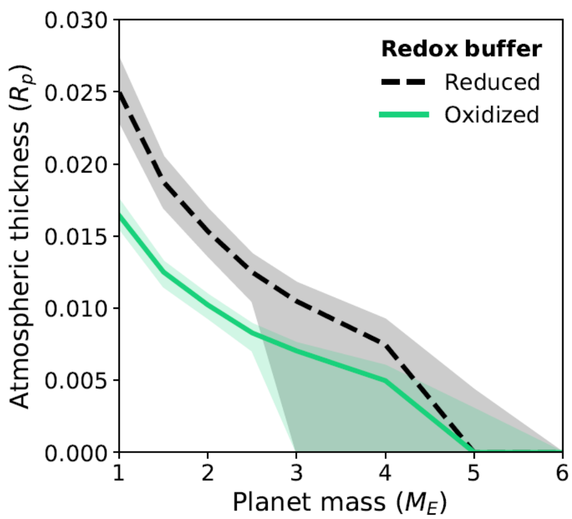

Figure 2: The mass-dependence of modelled atmospheric thickness, in units of planet radius, as predicted after 4.5 Gyr of mantle evolution, comparing reduced to oxidized mantles. Shaded area shows the 1σ variation across all simulations. At larger masses, even the puffier atmospheres start to be dwarfed by the large radius of the planet, and their relative thicknesses approach zero.

We show, however, that the redox state has an equally important role and leads to distinguishable atmosphere signatures for young atmospheres (i.e. with negligible alteration due to erosion and atmosphere chemistry) that can be used in the future to constrain the interior chemistry and potential for building up a habitable environment (Fig. 3).

The reduced redox state is especially relevant for outgassing of carbon dioxide, since in that case dissolution of carbonates into the melt is suppressed, and since gas speciation would favour CO over CO_2.

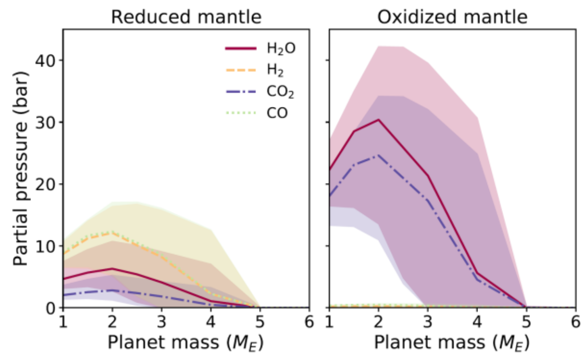

Figure 3: Change of modelled partial pressures for different gas species with 1σ variation depending on redox state and planet mass after 4.5 Gyr of mantle convection averaged over ~5000 simulations each.

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