Sublimation of refractory minerals in the gas envelopes of accreting rocky planets

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Motivation:

Due to the release of kinetic energy during the accretion process, the envelopes of an accreting protoplanets heats up. Here we study whether sublimation of refractory minerals will play a role during growth of a rocky planet by pebble accretion.

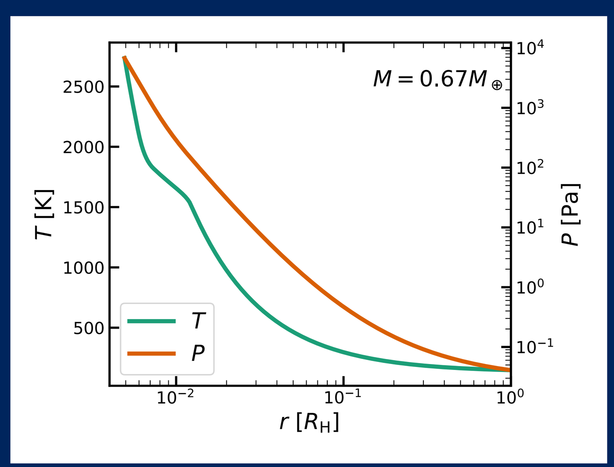

Figure 1: Temperature and pressure profile in the envelope of a planet with M = 0.67 $M_\oplus$.

Method:

We use a simple pebble accretion model to create a growth track of a planet with a final mass of M = 0.67 $M_\oplus$ following Johansen et al. (2019). The envelope structure of the planet is based on the equations of hydrostatic balance. We pick different mineral species representing ultra-refractories, silicates, iron, and moderately volatile minerals. We calculate their sublimation temperature from the supersaturation level

$$\ln S = -\Delta G/R_{gas}T_{sub} + \Sigma\, \nu_j \ln(P_j/P_{std}) = 0$$

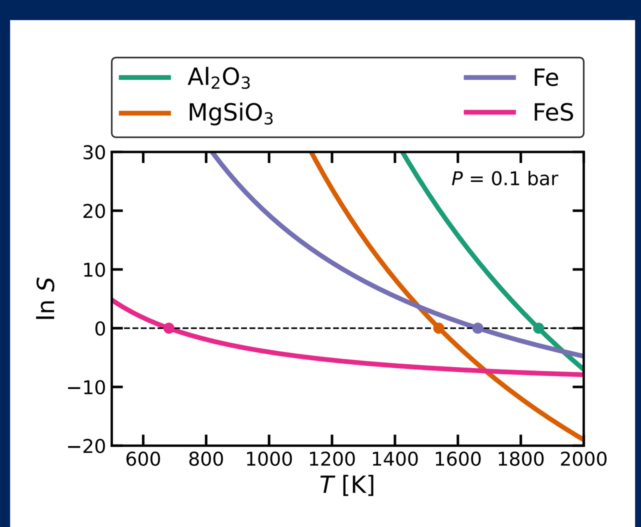

Figure 2: Natural logarithm of the supersaturation level for the different mineral species in a gas with solar nebulae composition from Lodders (2003). The pressure level corresponds to the inner region of a planetary envelope.

Results:

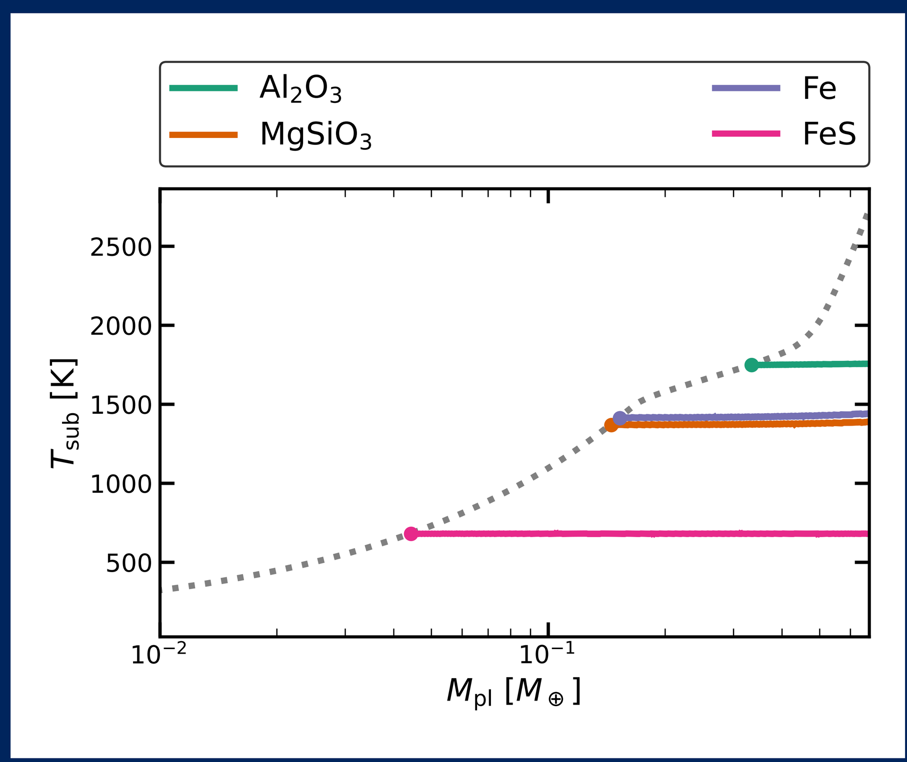

Figure 3: Sublimation temperatures of the representative mineral species. The dotted line shows the surface temperature of the planet as a function of its mass.

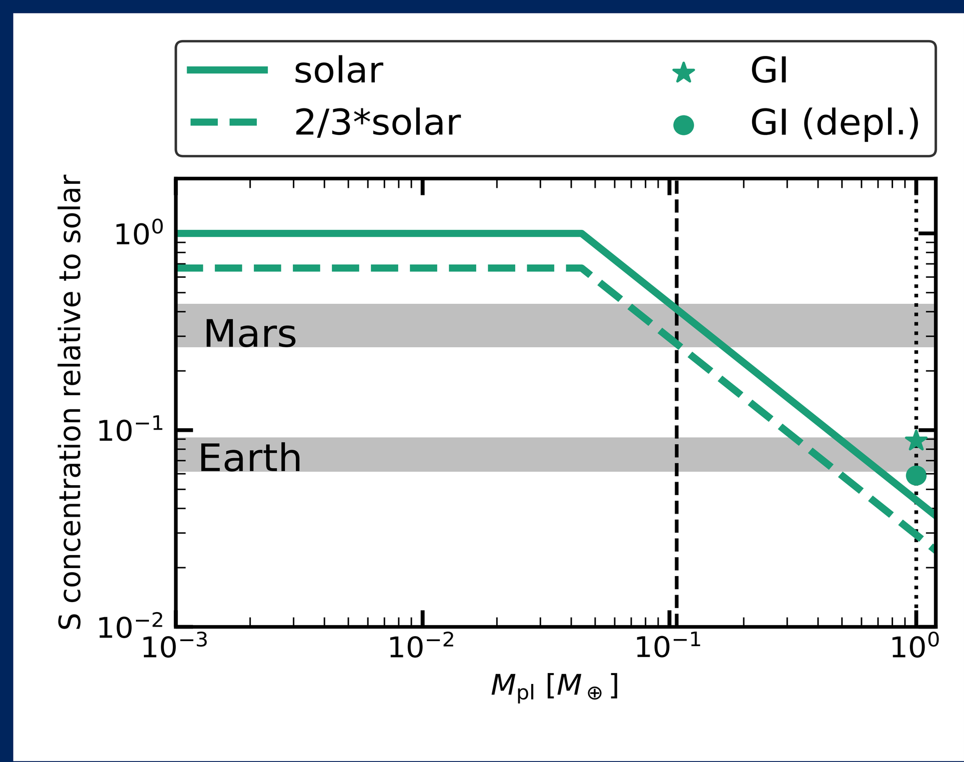

Figure 4: S concentration of a planet normalized to solar composition for two different pebble compositions under the assumption that all released S is lost from the planet. The estimated rage of bulk S concentrations of Mars and Earth are shown by the grey bands.

The protoplanet starts to bind an envelope once it reaches a mass of 0.01 $M_\oplus$. The envelope heats up from the bottom due to the accretion of pebbles. The sublimation temperature of FeS is already reached when the planet reaches a mass of 0.05 $M_\oplus$. Once the planet has grown to a mass of 0.5 $M_\oplus$ the envelope becomes hot enough to sublimate all representative mineral species considered.

Envelopes of planets embedded in the protoplanetary disk continuosly exchange gas with the surrounding disk (Ormel et al. 2015). The silicates and ultra-refractories sublimate deep in the envelope where they are protected from getting recycled back into the disk.

FeS on the other hand reacts with H_2 to form H_2S in the convective region of the envelope. The released H_2S will quickly move up to the Bondi radius where it will leave the envelope as part of the recyling flows. We therefore expect the S concentration in a planet to drop after the envelope reaches the sublimation temperature of FeS.

Both Earth and Mars are depleted in S compared to the solar composition. Our predicted S concentrations are in good agreement with the bulk S concentration of Mars. We also match the S concentration of bulk Earth if we take into account that Earth undergoes a giant moon forming impact. Our findings are therefore in favour of a formation of terrestrial planets by pebble accretion.

Take Home Message:

The envelopes around low mass rocky planets are hot enough to sublimate the incoming pebbles before they reach the surface. Volatile to moderately volatile elements are easily lost from the planet. **We thus expect the concentration of (moderately) volatile elements to be a decreasing function of planet mass in the pebble accretion scenario. This model explains the Sulphur content of both Earth and Mars.**

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