From clouds to crust: Cloud diversity and surface conditions in atmospheres of rocky exoplanets

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The surface composition of rocky planets outside of our solar system is very hard to be determined, especially if the planet has a cloud layer, which can potentially cover the entire planet. However, future observations will allow the investigation of the high atmospheric gas composition and can provide insights to the composition of potential clouds that are present. We want to link our understanding of these higher atmospheric conditions to the conditions at the surface. In other words: what can we learn about the crust composition from the clouds?

**Bottom to top atmospheric model**

In order to investigate this question, we build a quick and simple bottom to top atmospheric model, which is in contact with the crust underneath. This allows the study of atmosphere based on various surface conditions (Pressure, temperature, and composition).

![Diagram of atmospheric model](image)

**Figure 1:** Schematic view of the atmospheric model presented here. The bottom to top atmosphere is in chemical phase equilibrium with the surface. Thermally stable condensates are taken out of the atmosphere and the atmosphere is depleted with respect to the effected elements.

Our model is based on a crust-atmosphere interaction layer, which is assumed to be in chemical and phase equilibrium. The model is part of the equilibrium chemistry model GGchem. Based on the total element abundance $\epsilon_{tot}$, surface temperature $T_{surf}$ and surface pressure $p_{surf}$, the crust rock composition $\epsilon_{cond}$ is determined as well as the gas composition in the near crust atmosphere $\epsilon_{gas}(0)$. This gas composition provides the first layer for the atmospheric model.

Based on this atmosphere-crust interaction layer, we build a bottom to top atmosphere under the assumption of a polytropic atmosphere in hydrostatic equilibrium. In each atmospheric layer $i$, we solve the chemical phase equilibrium ($\epsilon_0(i) = \epsilon_{gas}(i) + \epsilon_{cond}(i)$). All thermally stable condensates are removed, which depletes the atmosphere above with respect to the effected elements (see also Figure 1). The remaining gas phase abundances are forming the total element abundances of the atmospheric layer above $\epsilon_0(i + 1) = \epsilon_{gas}(i)$.

**Water as part of the crust composition**

One of the major questions with respect to astrobiology is, whether a planet has liquid water at its surface. In [1], we show that the formation of liquid water is inhibited by the formation of phyllosilicates. These hydrated rocks incorporate OH into their lattice structure. Before water is a stable condensate, all phyllosilicates have to have formed.

**Cloud diversity**

Figure 2 shows the most abundant thermally stable condensates for models based on Bulk Silicate Earth and CI chondrite composition, for surface pressures of 1 bar and surface temperature ranging from 300 K to 1000 K. The thermally stable condensates can be separated into two different categories, high and low temperature condensates. The only condensate that is stable in both temperature regimes is graphite (C[s]).

For atmospheres with liquid water at the surface, water clouds are thermally stable throughout the atmosphere. However, models without water condensates as part of the crust still show conditions with thermal stability of water in higher parts of the modelled atmospheres. This shows that water clouds themselves are not necessarily indicative for water at the surface of the planet. A major constraint on the atmospheric height of the water cloud base is the hydration level of the models crust.
Atmospheric composition

In [4], we showed that the gas phase composition of atmospheres containing CHNO can be categorized into three different atmospheric types. The three resulting atmospheric types (triangle in Figure 3 top) show distinctive gas phase compositions (table Figure 3). These atmospheric types are independent of pressure, temperature (below 600 K) and overall Nitrogen content.

Although the atmospheric composition changes with increasing height, the atmospheric type in which the entire atmosphere falls is determined by the atmospheric type set by the near crust atmospheric composition. The atmospheric type does not change due to condensation in the atmosphere. However, significant changes in surface pressure and surface temperature can result in a change of an atmospheric type for the entire atmosphere.

Summary

The fast and simple atmospheric model presented provides the opportunity to investigate the influence of changes in total element abundances on atmospheric composition and thermally stable cloud condensates.

Water can only form as a condensate at the planetary surface if the phyllosilicates are saturated. In the atmosphere above such a surface, water clouds are thermally stable in the crust-atmosphere contact layer as well as the atmospheric layers above, the water cloud base touches the ground. Models without water at the surface still show thermal stability of water in their respective atmospheres. This underlines that the presence of water condensates in the atmosphere does not necessarily imply water at the surface of the planet.

References

[1] Herbort, O., et al., 2020, A&A, 636
[2] Woitke, P., et al. 2018, A&A, 614
[3] Herbort, O., et al. submitted to A&A
[4] Woitke, P., et al. 2021, A&A, 646