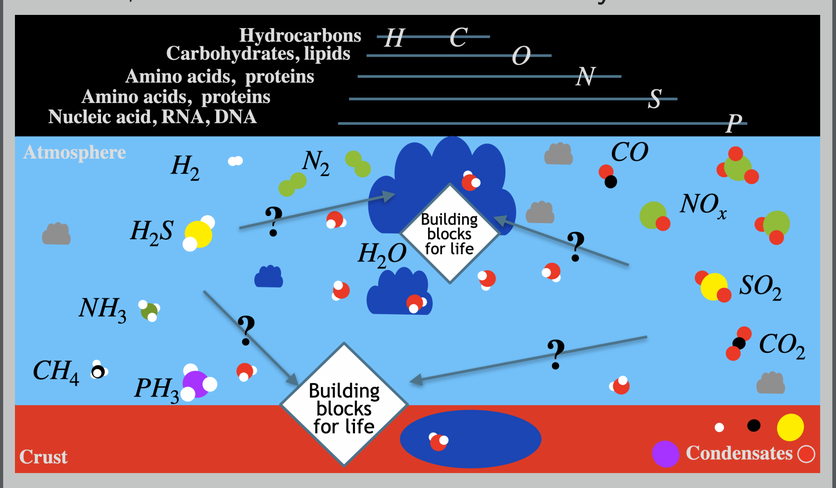
Nutrient availability constrains on habitability of rocky worlds

Oliver Herbort[1]
P. Woitke[2] Ch. Helling[2] A. L. Zerkle[3]
1) Institute for Astrophysics, University of Vienna
2) Institut für Weltraumforschung Graz
3) Blue Marble Space Institute of Science

Introduction - Science questions

- Liquid water, the most fundamental aspect necessity for life as we know it, is not only possible at the planetary surface, but also in the atmosphere in form of clouds
  - ▷ Theoretical concept of aerial biospheres
- In order for life to form and sustain the presence of nutrients (CHNOPS) and metals are needed
- Do atmospheres of rocky worlds allow for the presence of CHNOS?
- If so, in what chemical state are they?



Defining nutrient availability

The number of nutrients present in the atmosphere at a given point defines the nutrient availability level

Nutrient availability	H_2O[l]	C	N	S	P
Not habitable	✘	-	-	-	-
Level 0	✔	✘	✘	✘	✘
Level 1C	✔	✔	✘	✘	-
Level 1N	✔	✘	✔	✘	-
Level 1S	✔	✘	✘	✔	-
Level 2CN	✔	✔	✔	✘	-
Level 2CS	✔	✔	✘	✔	-
Level 2SN	✔	✘	✔	✔	-
Level 3	✔	✔	✔	✔	-
Level 3red	✔	red	red	red	-
Level 3ox	✔	ox	ox	ox	-
P	✔	-	-	-	✔

✔: element is present in a molecule at concentration levels above $\mathbf{10^{-9}}$ in the gas phase
✘: no molecules carrying this element are present at concentrations $> \mathbf{10^{-9}}$
'-': element does not matter for the definition of the respective level
'red': reduced form present
'ox': oxidised form present

Conclusion

Nutrient availability:
- Reduced forms of C N S present in most atmospheres at water cloud base
- Lack of P and metals
  - ▷ Updraft from surface or delivery necessary

Implications for aerial biospheres:
- Most fundamental nutrients present with thermally stable liquid water clouds
- HF and HCl only other non-CHNOS species

Atmospheric model

- Bottom to top atmosphere coupled to a crust- atmosphere layer in chemical phase equilibrium (Herbort et al., 2022)
- Based on GGchem (Woitke et al., 2018)
- Crust-atmosphere equilibrium (Herbort et al., 2020)
- Assuming a hydrostatic, polytropic atmosphere
  - ▷ All atmospheres presented reach $T = \mathbf{300}$ K at $p_{\rm gas} = \mathbf{1}$ bar
- Equilibrium chemistry with equilibrium condensation in every atmospheric layer i

$$\epsilon_0^i = \epsilon_{\rm gas}^i + \epsilon_{\rm cond}^i$$

  - ▷ Every thermally stable condensate $\epsilon_{\rm cond}$ is removed from the atmosphere, so that no molecule is supersaturated throughout the atmosphere
- Gas phase of one layer becomes the total element abundance of the layer above $\epsilon_{\rm gas}^i = \epsilon_0^{i+1}$

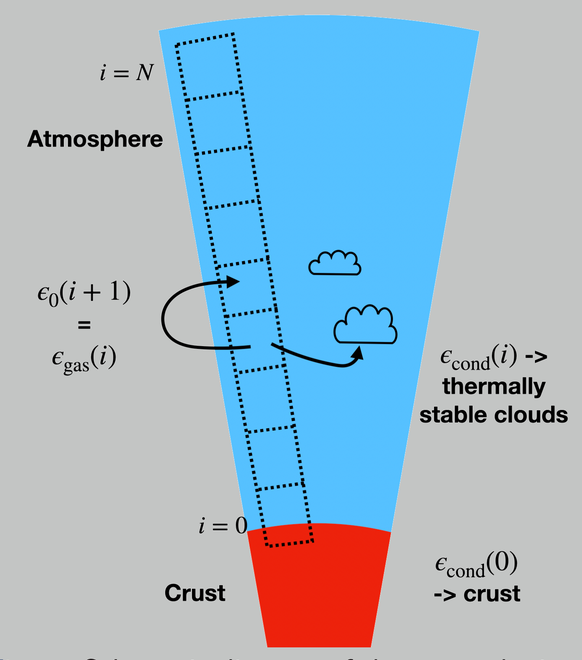


Figure: Schematic diagram of the atmospheric model. Thermally stable condensates are removed from the atmosphere.

Investigating one atmospheric model

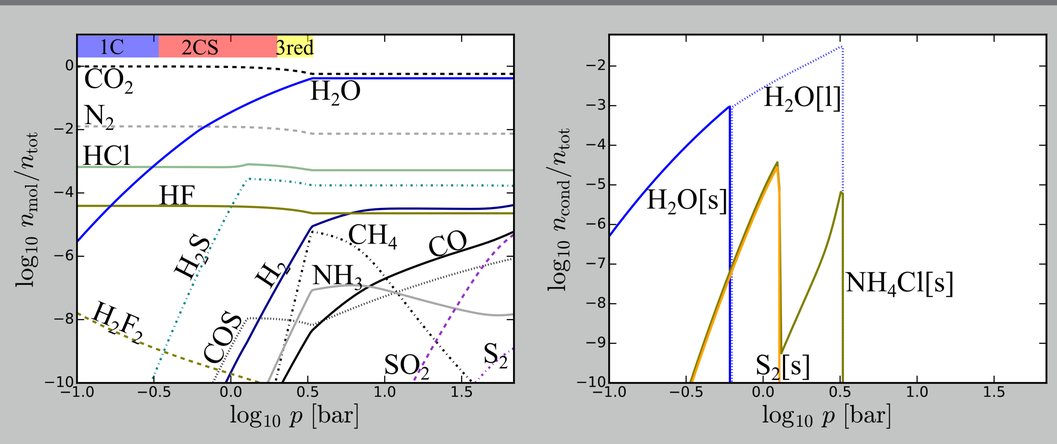


Figure: **Left panel:** Gas-phase composition of the model atmosphere with the indicated habitability levels at the top.
Right panel: Thermally stable cloud condensates in the model atmosphere.

$T_{\rm surf} = \mathbf{700}$ K, $p_{\rm surf} = \mathbf{70}$ bar, Continental Crust (Schaefer et al., 2012)
- overall CO_2, H_2O, N_2 dominated atmosphere
- Reduced forms of C N S present at water cloud base!
- lack of N at lower pressures, caused by NH_4Cl condensation
- HCl and HF concentrations $> \mathbf{10^{-4}}$

Changing surface compositions and temperature range

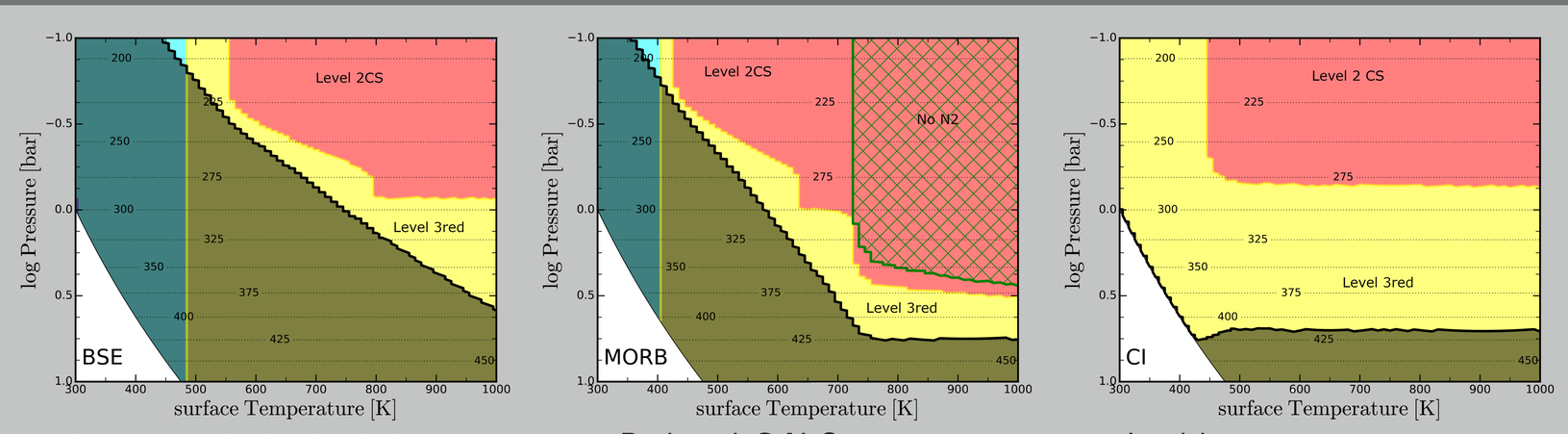


Figure: Nutrient availability levels for different total element abundances, varying surface temperatures.

Bulk Silicate Earth (Schaefer et al., 2012)
- No water at the surface
- H_2O clouds in reduced environment

Mid Oceanic Ridge Basalt (Arevalo & McDonough, 2010)
- High $T_{\rm surf}$ without any N_2 in upper atmosphere!

Carbonaceous (CI) chondrite (Lodders et al., 2009)
- Liquid water at the surface

- Reduced C N S common at water cloud base
- General lack of bioavaiable N at lower pressures, Level 2CS
- N_2 not present in case of high surf temp of MORB compositions.

Chemical state of different elements

Carbon
- Mostly in CO_2, CH_4

Nitrogen
- NH_3 dominant
- Is N_2 available for prebiotic chemistry?

Sulphur
- present as H_2S and SO_2
- H_2S also in CO_2 dominated environments

Phosphorus
- Not present in the atmosphere, bound in condensates
- Limitation for biosphere?

Metals
- Not present in the atmosphere at habitable temperatures, delivery needed

Halides
- Prominent in many atm.
- Causes acidic environment

References

Arevalo, R. & McDonough, W. F. 2010, Chemical Geology, 271, 70
Herbort, O., Woitke, P., Helling, C., & Zerkle, A. 2020, A&A, 636
Herbort, O., Woitke, P., Helling, C., & Zerkle, A. L. 2022, A&A, 658, A180
Lodders, K., Palme, H., & Gail, H. P. 2009, Landolt Börnstein, 4B, 712
Schaefer, L., Lodders, K., & Fegley, B. 2012, Astrophys. J., 755, 41
Woitke, P., Helling, C., Hunter, G., et al. 2018, A&A, 614, A1

Contact: oliver.herbort@univie.ac.at