The impact of sulphur and phosphorus on atmospheric heating and cloud formation in sub-Neptunes

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Motivation

Little is known about the compositions of sub-Neptunes and their atmospheres, but JWST sheds first light into the atmospheres of some cases like K2-18b, K2-141b or 55 Cnc e. The sulphur (S) and phosphorus (P) fraction varies strongly for different stars. This could impact the amount of P and S present in planetary atmospheres. Outgassing can also enrich atmospheres with these volatiles. We run a grid search to explore possible temperature structures, atmospheric compositions and cloud species of hot sub-Neptunes. We find temperature inversions in atmospheres which are reducing and rich in sulphur and phosphorus. Could condensates form in atmospheres enriched in those species?

Methods

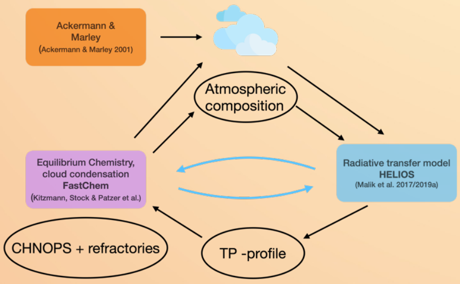

Fig. 1: Diagram of the computational framework used for this work : coupling of FastChem 3 with HELIOS, cloud model from Ackermann & Marley (2001)

- Grid search for compositions and atmospheric structures of sub-Neptunes
- elemental composition: refractories in solar abundances, varying the CHNOPS elemental ratios looking at:
  - **CO-dominated** atmospheres
  - **N-dominated** atmospheres
  - **H-dominated** atmospheres

Important opacities

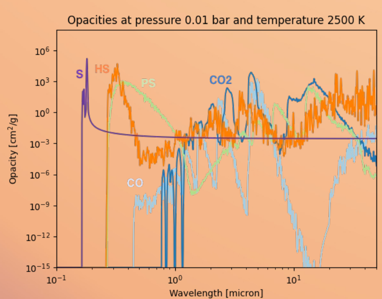

Fig.3: Opacities of the major heating and cooling components in the two atmospheres N_1b (PS poor) and N_1c (PS rich)

- CO and CO_2 absorb at wavelengths larger than 1 micron, keeping the atmosphere cool if abundant (see Fig. 3)
- PS, S and HS strongly absorb at shorter wavelengths. This causes heating if they are abundant

If you are interested in reading more about sulphur in atmospheres of exoplanets, scan this QR code !

Two examples from the grid search: A PS poor and a PS rich atmosphere

- Fig. 3 shows temperature-pressure profiles and major species of two cases from the grid search
- both cases are N-dominated with C/O=1
- Case 1: **sulphur and phosphorus poor** (P/H = 10^{-6}), **decrease in temperature** of 1000 K between 10^{-1} and 10 bar. Some major species are CO, N_2, CO_2, H_2S
- Case 2: **sulphur and phosphorus rich** (P/H = 10^{-3}), **temperature inversion** with increase of 1300 K around similar altitudes. Some major species are N_2, P, S, PS, CO

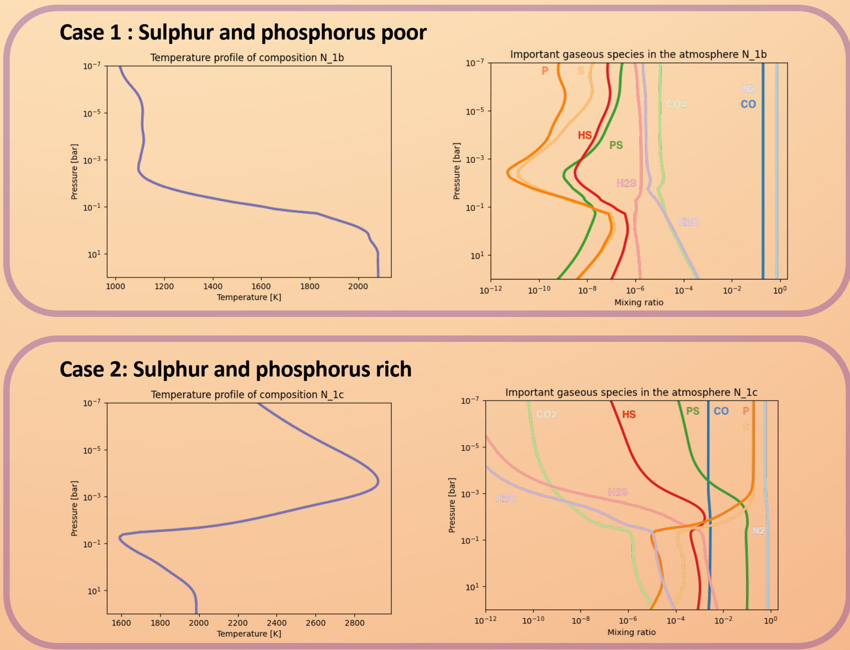

Fig.2: TP profiles and mixing ratios in a PS poor and a PS rich atmosphere

What does this mean for cloud formation ?

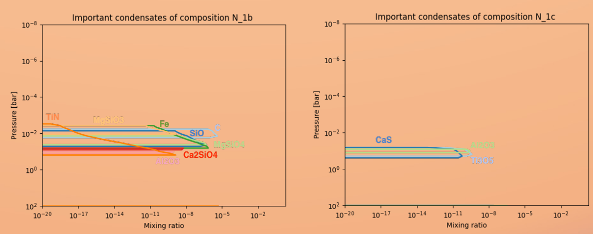

Fig.4: Condensates in a PS poor atmosphere (N_1b) and a PS rich atmosphere (N_1c)

- Condensates can form in the region of a steep temperature gradient, see Fig. 4. The list of condensing species is large.
- No condensate reaches mixing ratios above 10^{-9} in a phosphorus and sulphur rich model because of the temperature inversion.

Conclusions

- PS, HS and S form in reduced, sulphur and phosphorus rich atmospheres. NOTE: if the oxygen content increases this can change
- PS, HS and S heat the atmosphere and can create temperature inversions.
- Condensates are less likely to form in reduced, sulphur and phosphorus rich atmospheres.
- We need more optical data to assess the effect of all condensate/cloud species on the temperature structure and to conclude on their observability.