ÖAW — AUSTRIAN ACADEMY OF SCIENCES

DISEQUILIBRIUM CHEMISTRY ON GAS-GIANT EXOPLANETS

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INTRODUCTION

Statistics of known exoplanets show a range in their properties such as equilibrium temperature, mass, radius, and proximity to host star. To better understand observations of these exoplanets, one can employ atmospheric models and explore the potential atmospheric composition of these exoplanets and their observable signatures. These models can be run under different assumptions regarding the thermodynamic state of the atmosphere.

WASP-69b is a Jupiter-like exoplanet that has an orbital period around its host star of $\sim$ 4 days. It has been observed to have CH_4, NH_3, CO, H_2O and C_2H_2 in its atmosphere (Guilluy et al. 2022). Of these, CH_4, NH_3 and C_2H_2 are not expected to be produced in large abundances in the atmosphere for thermochemical equilibrium conditions.

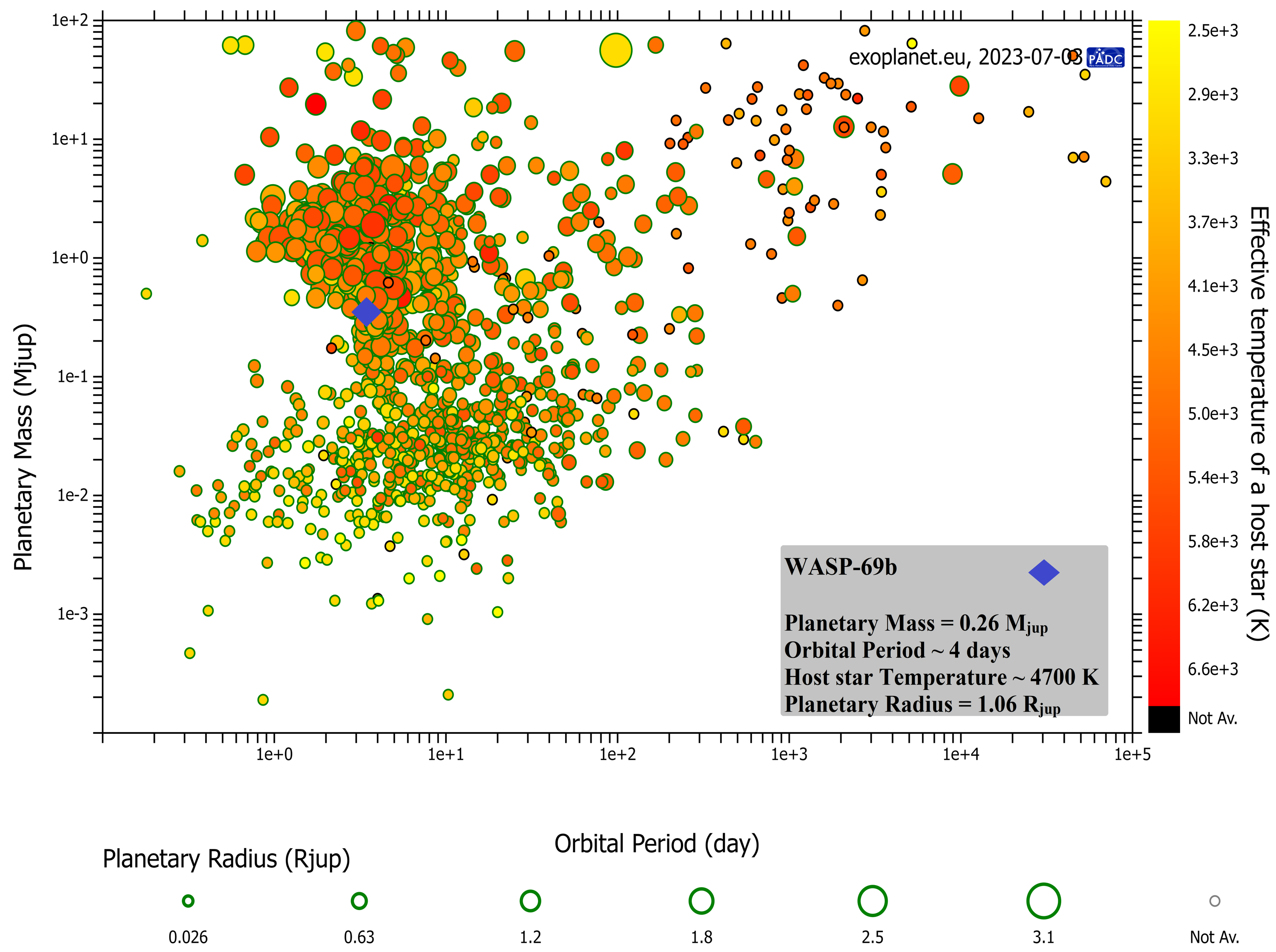

Figure 1: Population of known exoplanets. Gas-giant WASP-69b is highlighted in plot.

The aim of this study is to identify what processes form the observed atmospheric chemistry of exoplanet WASP-69b. Two key processes that can drive the conditions in the atmosphere out of equilibrium are **vertical transport** of gases and **stellar-radiation driven chemistry** (Moses 2014).

MODELLING

The 1-dimensional, diffusion-photochemistry code ARGO (Rimmer Helling 2016) is used to model the gas-phase composition of WASP-69b's atmosphere. ARGO solves the 1D continuity equation for each chemical species i,

$$\frac{\partial n_i}{\partial t} = P_i - L_i - \frac{\partial \phi_i}{\partial z} \quad (1)$$

The terms on the right-hand side of the equation represent the production, loss, and vertical flux of species i respectively. ARGO follows a single parcel of gas as it moves up through the atmosphere, and then returns downwards (Figure 2). The atmosphere is then irradiated and the cycle is repeated until the chemistry reaches a steady state. For the chemical network, 480 chemical species and over 6000 reactions are used.

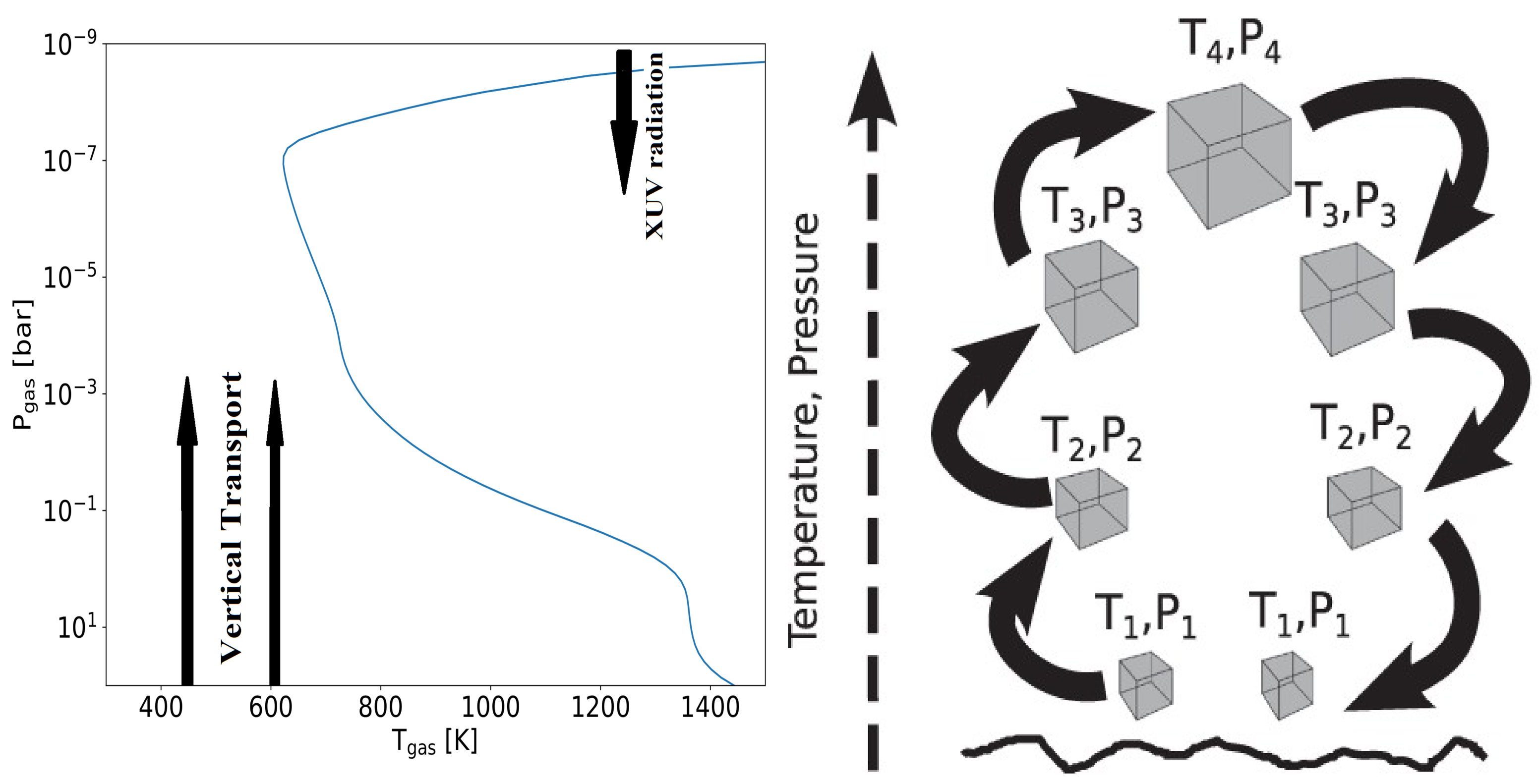

Figure 2: Left: the pressure temperature profile for our models of WASP-69b. Right: Pictorial representation of the motion of a parcel of gas through the planetary atmosphere in the model ARGO.

CH_4, NH_3 DOMINATED BY VERTICAL TRANSPORT

As gas is transported through the atmosphere, the concentration of a species can become 'quenched' when the timescale of vertical transport becomes smaller than the chemical timescales of reactions involving the species. The concentration of that species then remains fixed at the quenched value. This process occurs where the temperature or pressure of the atmosphere is low enough that reactions are not equally efficient in the forward and reverse directions (Moses 2014). We find that:

- The effect of quenching is most clearly seen in CH_4 and NH_3.
- CH_4 and NH_3 are destroyed in upper atmosphere by XUV radiation.
- Quenched species that are parent molecules to other species can enhance the latter's abundances. For example, quenching of CH_4 and NH_3 also increases HCN abundances.

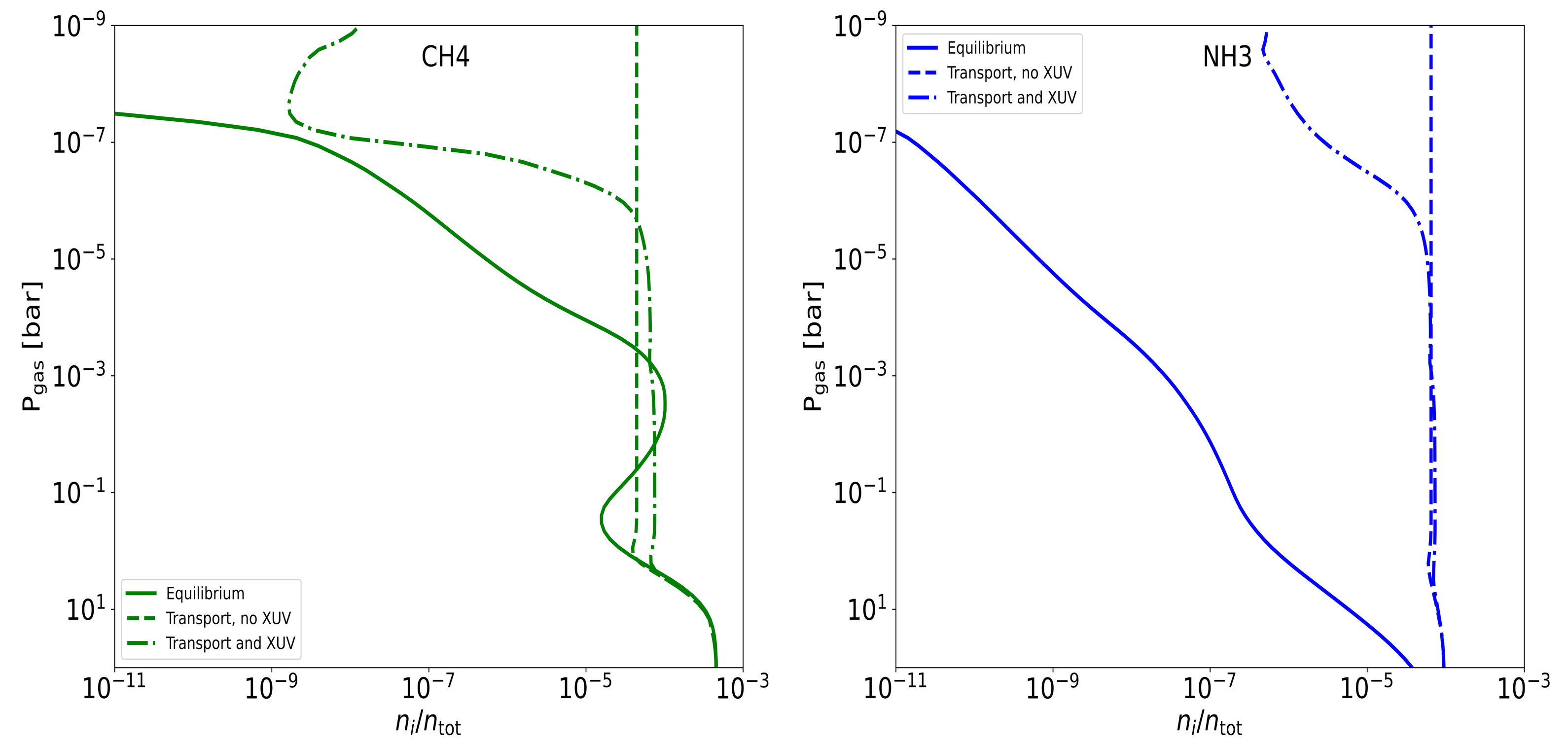

Figure 3: Concentrations $\frac{n_i}{n_{tot}}$ for CH_4 and NH_3 in our model under different assumptions about the chemistry and transport. CH_4 and NH_3 abundances are 'quenched' to greater than equilibrium values.

C_2H_2, HCN INCREASED BY PHOTOCHEMISTRY

Stellar UV and X-ray photons are the main drivers of photochemistry in planetary atmospheres. The dissociation of molecules, for e.g. CH_4, NH_3, and CO, in the upper atmosphere by radiation releases atoms which then interact to form new chemistry.

- C_2H_2 and HCN benefit from the photochemical release of H,C, and N.
- At lower altitudes C_2H_2 is recycled back into CH_4.
- HCN retains higher abundances than CH_4 at high altitutes.

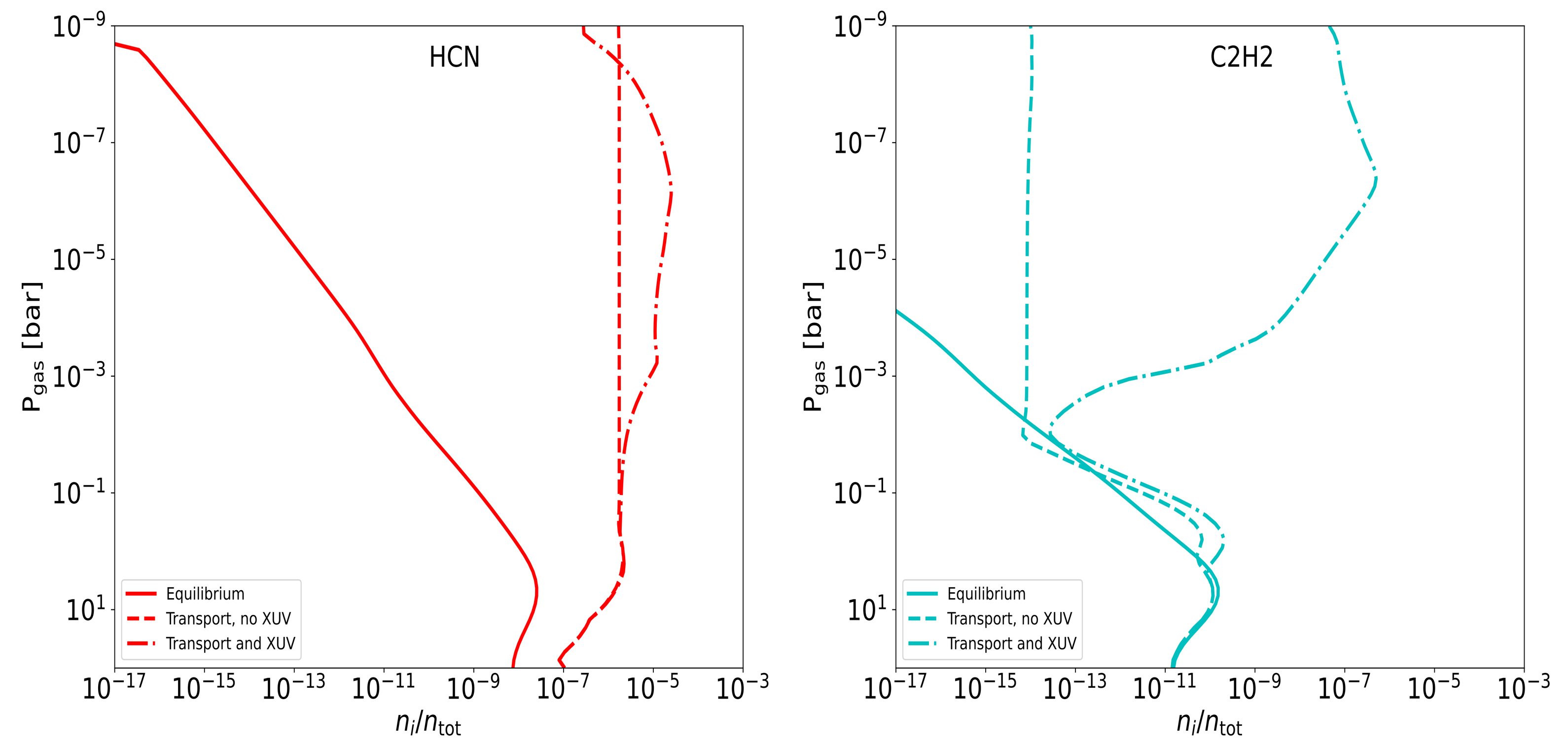

Figure 4: Concentrations $\frac{n_i}{n_{tot}}$ for HCN and C_2H_2 in our model under different assumptions about the chemistry and transport. Stellar radiation driven chemistry increases the concentrations of HCN and C_2H_2.

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SUMMARY

- Vertical transport of gases and photochemistry can significantly drive an exoplanet's atmospheric composition out of equilibrium.
- In WASP-69b's atmosphere, CH_4 and NH_3 abundances are most affected by quenching whereas HCN and C_2H_2 abundances are increased by photochemistry.

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References

Guilluy, G., et al. 2022, *AA*, 665; **Rimmer, P. B. and Helling, C.**, 2016, *ApJ* 224, no. 1. ; **Moses, J. I.**, 2014, *Philos. Trans. Royal Soc.*, 372.