ÖAW — AUSTRIAN ACADEMY OF SCIENCES

Cloud regimes on gas-giant exoplanets*

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* Helling et al., A&A 671, 2023 and Lewis et al., TU Graz PURE, 2022

Introduction

The diverse population of exoplanet systems spans a wide range of thermodynamic and chemistry regimes. As a result the properties of exoplanet atmospheres and the clouds present are expected to vary substantially. We apply a hierarchical approach to explore global cloud formation in gas-giant planet atmospheres.

We utilise a grid of cloud-free 3D General Circulation Models (GCMs) of tidally locked hot Jupiter gas-giant exoplanets with radius $R_{\rm p} = 1.35\ {\rm R_{Jup}}$ and surface gravity $\log_{10}\left(g_p\,[\rm cm\,s^{-2}]\right) = 3$ (Baeyens et al., MNRAS 505, 2021). The grid spans model planets orbiting main sequence F, G, K, and M stars, with planetary equilibrium temperatures $T_{\rm eq} = 400 - 2600$ K. We extract 1D $(p_{\rm gas}, T_{\rm gas}, v_z)$-profiles from each of the GCMs as input to a kinetic cloud model which is combined with equilibrium gas phase chemistry.

Trends in microphysical properties

Integrated properties allow us to study trends in global properties of cloud formation. We compute the column integrated nucleation rate and the column integrated, number density weighted, surface averaged mean particle size,

$$\langle\langle a\rangle_{\rm A}\rangle = \frac{\int_{z_{min}}^{z_{max}} n_d(z)\langle a\rangle_{\rm A}(z)dz}{\int_{z_{min}}^{z_{max}} n_d(z)dz}$$

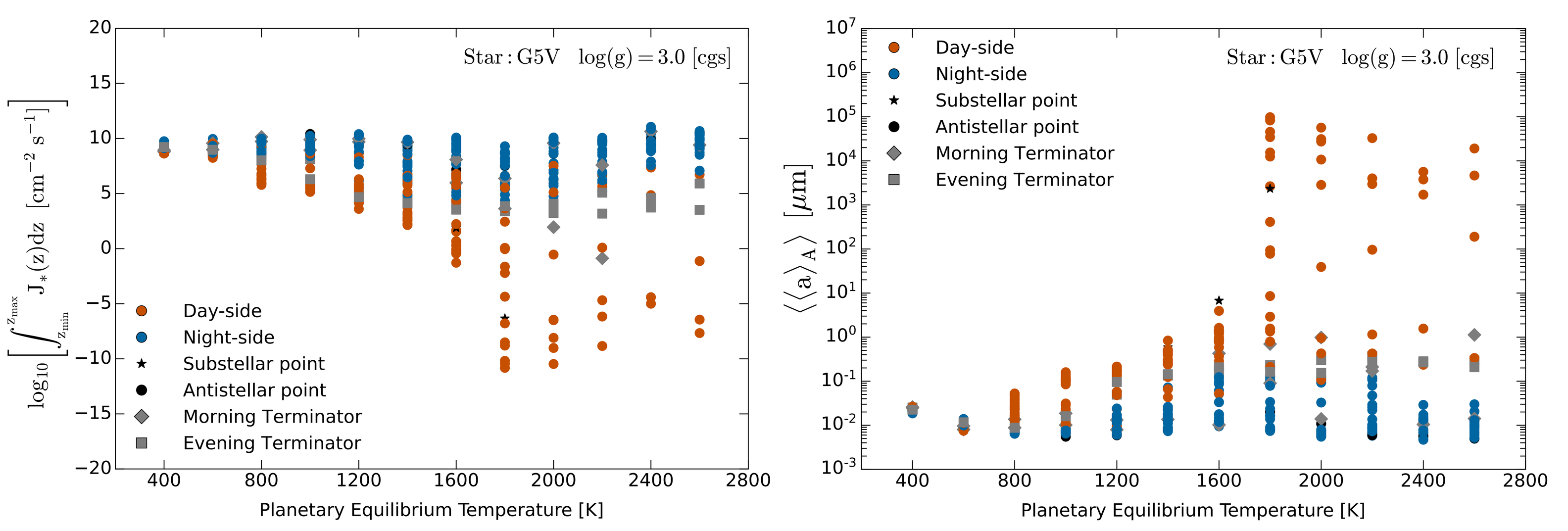

Figure 1: Column integrated microphysical cloud properties. **Left:** Total nucleation rate. **Right:** Surface averaged mean particle size.

The nightside nucleation remains broadly constant across the full range of $T_{\rm eq}$. In contrast, there is a reduced nucleation on the dayside for exoplanets with a higher planetary equilibrium temperature. This results in significantly less dayside cloud formation. Furthermore, there is increased variation in average particle size on the dayside with increased $T_{\rm eq}$. For lower $T_{\rm eq}$ planets global average particle sizes are $\langle\langle a\rangle_{\rm A}\rangle \sim 10^{-2} - 10^{-1}\ \mu$m, whereas for higher $T_{\rm eq}$ planets $\langle\langle a\rangle_{\rm A}\rangle \sim 10^{-2} - 10^{5}\ \mu$m. At $T_{\rm eq} \sim 1600$ K a strong day-night asymmetry in the both the nucleation rate and the average particle size emerges.

Highly mixed cloud particles

The expected composition of the cloud particles depends on local thermodynamic conditions and hence changes throughout the atmosphere.

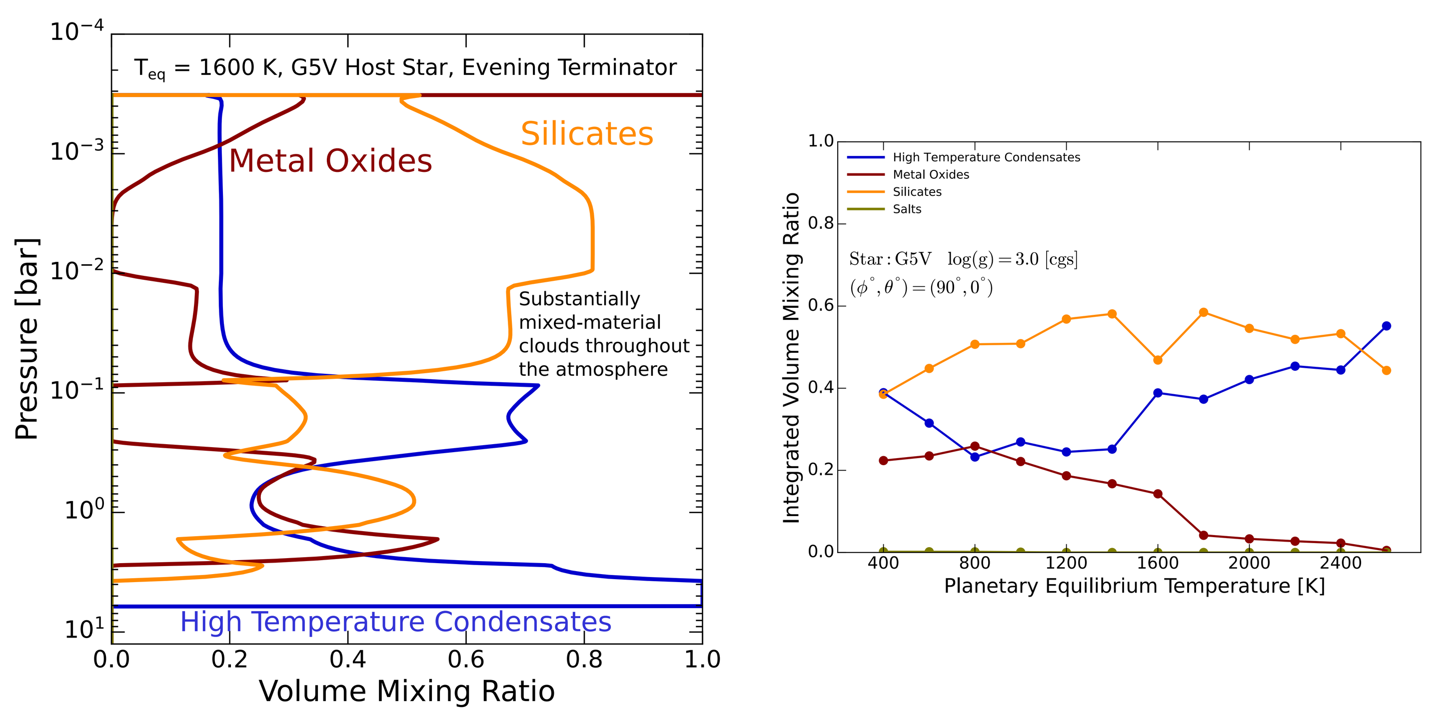

Figure 2: Mixed composition of cloud particles at the evening terminator of exoplanets orbiting a G-type star. **Left:** Variation in the composition of cloud particles throughout the atmosphere for the $T_{\rm p,\,eq} = 1600$ K model. **Right:** Normalised column integrated volume fractions

Throughout the atmosphere the local fraction of silicates ($MgSiO_3$[s], Mg_2SiO_4[s], Fe_2SiO_4[s], $CaSiO_3$[s]), metal oxides (SiO[s], SiO_2[s], MgO[s], FeO[s]), and high temperature condensates (TiO_2[s], Fe[s], FeS[s], Al_2O_3[s], $CaTiO_3$[s]) changes. Salts (KCl[s], NaCl[s]) do not contribute significantly. The cloud particles are highly mixed in composition at all equilibrium temperatures. The fraction of each condensate group varies substantially with depth in the atmosphere. Integrated over the whole atmosphere column, silicates tend to dominate the cloud composition. With increasing $T_{\rm eq}$ the fraction of metal oxides is expected to decrease while the fraction of high temperature condensates increases.

Cool, *Transition*, and *Hot* Exoplanet Atmospheres

We find that exoplanet atmospheres can be broadly categorised into three regimes: *cool*, *transition*, and *hot*.

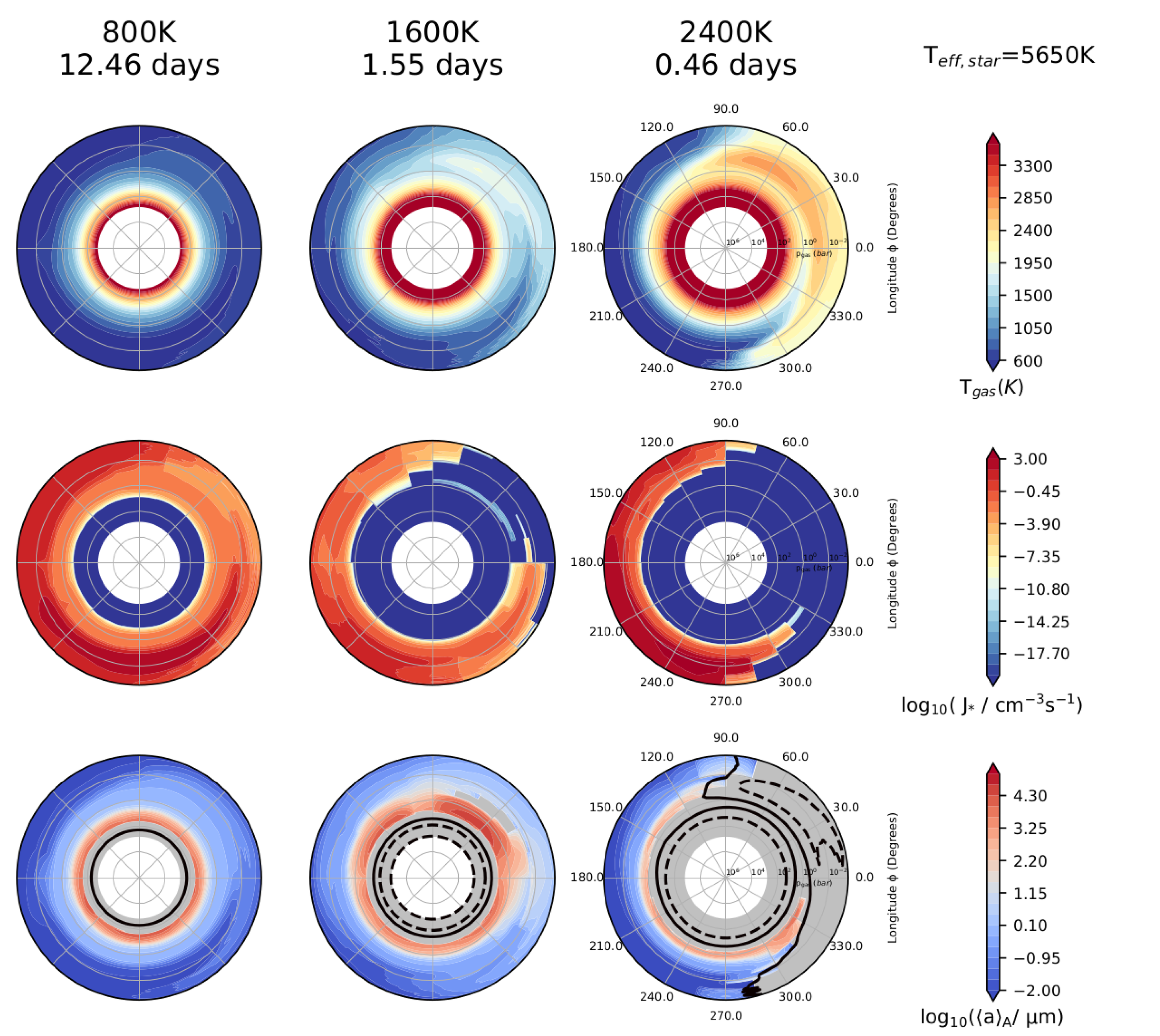

Figure 3: Cloud and atmosphere properties in the equatorial plane for a *cool* ($T_{\rm p,\,eq} = 800$ K, $P_{\rm rot} = 12.46$ days), *transition* ($T_{\rm p,\,eq} = 1600$ K, $P_{\rm rot} = 1.55$ days), and *hot* ($T_{\rm p,\,eq} = 2400$ K, $P_{\rm rot} = 0.46$ days) tidally locked gas-giant planet orbiting a G-type star. **Top row:** Atmospheric gas temperature. **Middle row:** Total nucleation rate. **Bottom row:** Surface averaged mean cloud particle size. The solid and dashed black contours show where the degree of thermal ionisation, f_e, of the gas is 10^{-7} or 10^{-6}, respectively.

Cool atmospheres ($T_{\rm p,\,eq} \leq 1200$ K)

- Homogeneous nucleation rate and global cloud coverage.
- Global average cloud particle sizes $\lesssim 1\ \mu$m.
- Globally constant mean molecular weight and low thermal ionisation.
- Example exoplanets: WASP-39 b and HATS-6 b.

Transition atmospheres ($T_{\rm p,\,eq} = 1400 - 1800$ K)

- Patchy nucleation rate and partial cloud coverage.
- Globally varied cloud particle sizes $1 - 10^{3}\ \mu$m.
- Globally constant mean molecular weight and low thermal ionisation.
- Example exoplanets: HD 209458 b and WASP-43 b.

Hot atmospheres ($T_{\rm p,\,eq} \geq 2000$ K)

- Nightside localised nucleation and cloud coverage.
- Average night-side cloud particles sizes $\lesssim 1\ \mu$m.
- Strong day-night contrast in mean molecular and a dayside thermal ionisation in the upper atmosphere.
- Example exoplanets: WASP-121 b and WASP-18 b.

SUMMARY

- Microphysical properties of cloud particles change significantly between exoplanets with different $T_{\rm eq}$. Higher $T_{\rm eq}$ exoplanets have a wide variation in nucleation rates and particle sizes between the dayside and nightside.
- Exoplanet clouds are expected to be highly mixed condensates rather than particles of a single condensate.
- Silicates tend to dominant the cloud particle composition. The fraction of high temperature condensates and metal oxides changes with $T_{\rm eq}$.
- Exoplanet atmospheres can be broadly classified into three regimes, based on their global cloud and gas phase properties.

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