ÖAW – AUSTRIAN ACADEMY OF SCIENCES

EXOPLANET WEATHER AND CLIMATE

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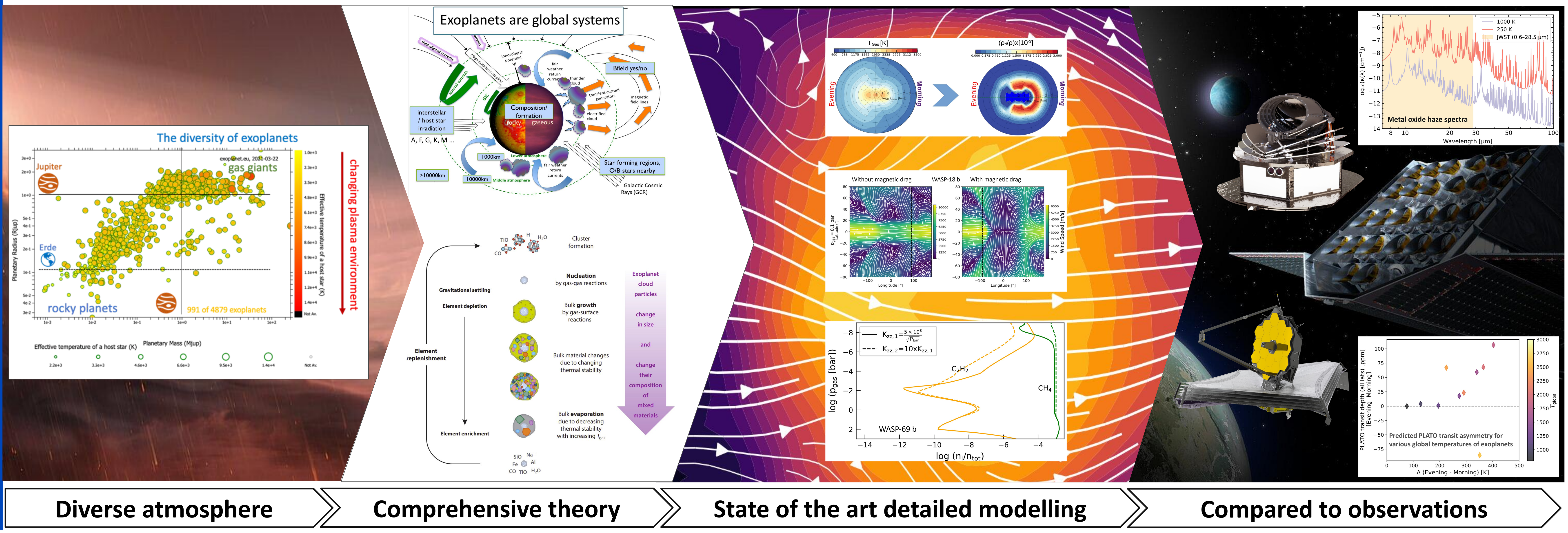
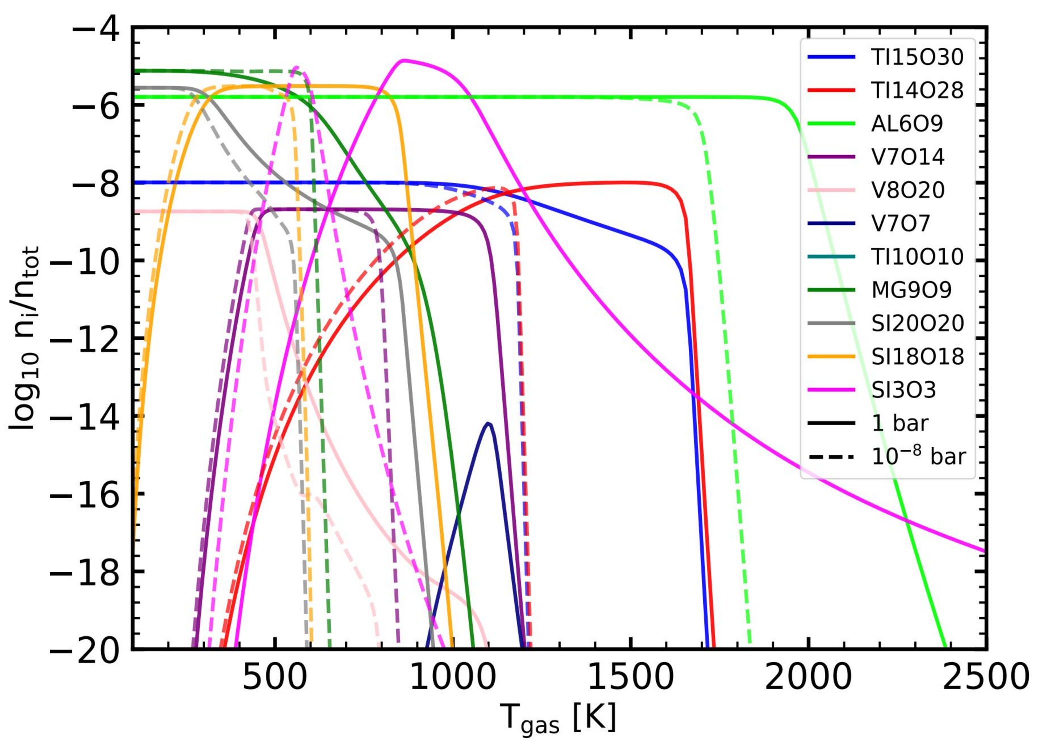


RESEARCH HIGHLIGHTS

Until now, more than 6,000 exoplanets are known, but many of their atmospheres still puzzle us. Current observations provide enough detail to drive theoretical understanding and challenge our existing models. In our group, we develop and study the following theoretical frameworks:

- **Microphysical cloud formation model** for diverse atmospheres.
- **Chemical kinetics model** that includes photochemistry, planetary lightning, cosmic rays, and dynamical mixing.
- **ExoRad 3D general circulation model** with non-gray radiative transfer, coupled with magnetic fields, chemistry, and cloud processes.
- **Machine learning (ML)** assisted, interpretable data pipelines enable a fast and reliable understanding of the complex planetary atmosphere.

CLOUD FORMATION IN DIVERSE EXOPLANET

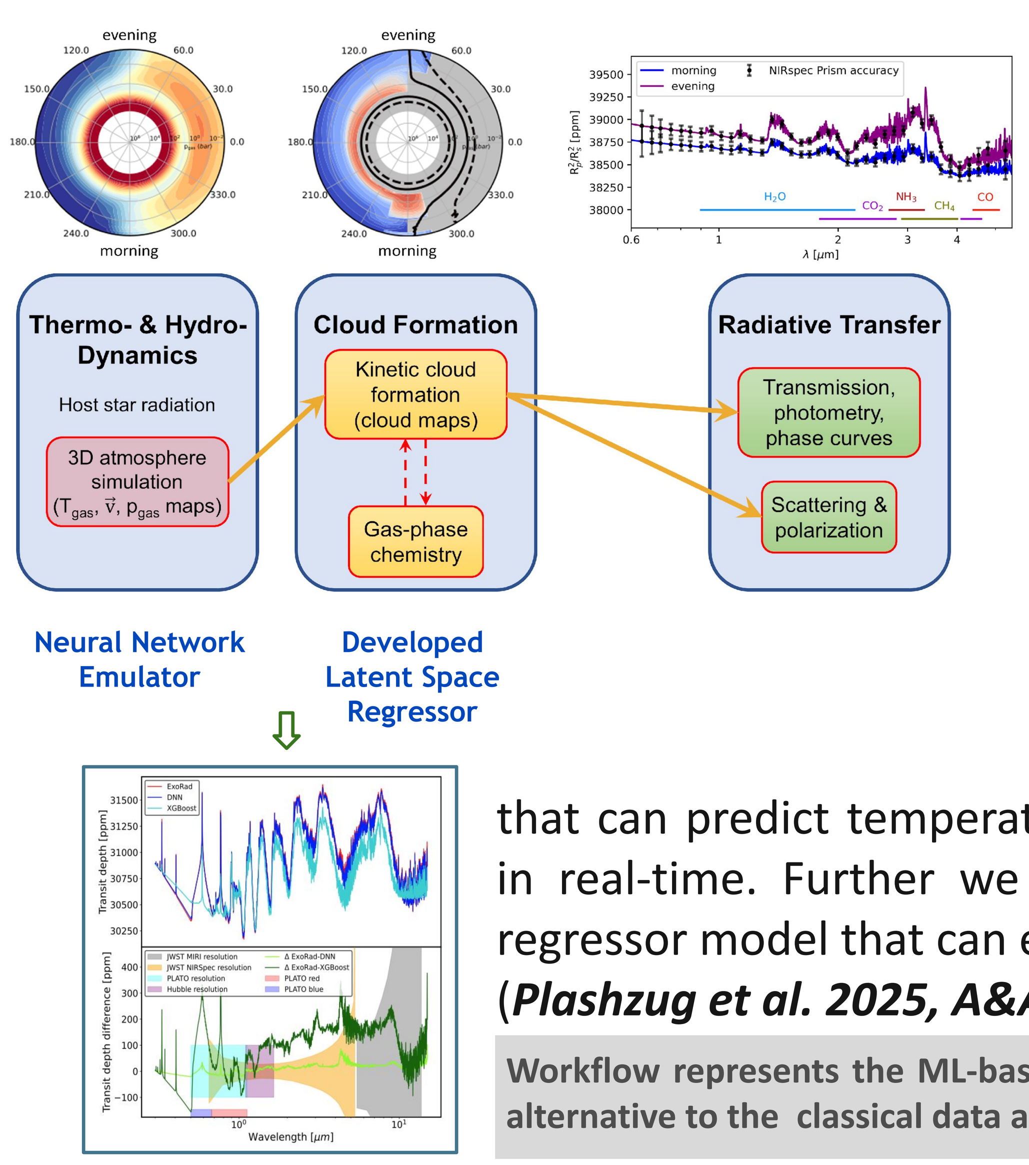


Number densities of most abundant metal oxide clusters.

Cloud particles form through condensation on small dust grains. In gaseous exoplanets, these particles originate when gaseous metal oxide clusters collide and combine to form larger clusters. As the clusters grow, they eventually reach a size that allows a phase transition from the gaseous to the solid state, acting as cloud condensation nuclei for metal hazes.

While the formation of larger clusters is generally favored at lower local gas temperatures, certain metal oxide species can still form substantial clusters even at temperatures around 2000 K. This enables the presence of cloud particles in the atmospheres of hot exoplanets.

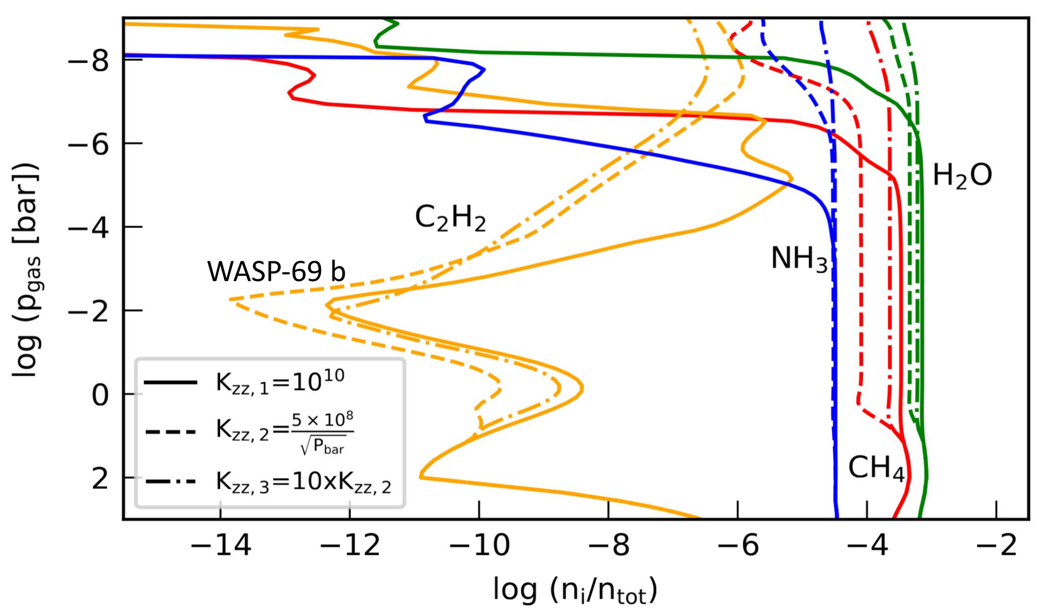
ML FRAMEWORK IN CLIMATE MODEL



We harness the potential use of ML models to facilitate the exploration of diverse exoplanet climate regimes. It transforms the classical use of the complex atmospheric models into an ML-driven data interpretation pipeline led by in-depth physio-chemical models. We have already developed a neural network emulator that can predict temperature-pressure profiles nearly in real-time. Further we developed a latent space regressor model that can emulate the cloud properties (*Plashzug et al. 2025, A&A*).

Workflow represents the ML-based data interpretable pipeline as an alternative to the classical data analysis components.

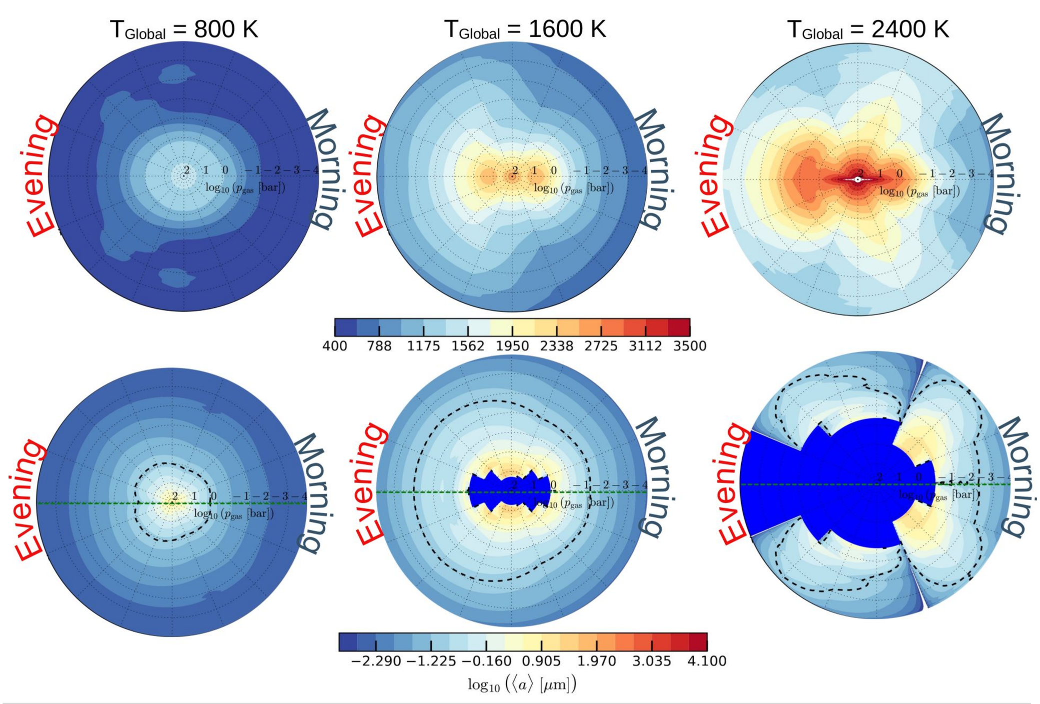
NON-EQUILIBRIUM ATMOSPHERIC CHEMISTRY



How the vertical mixing changes the amount of key molecules in an oxygen-rich gas-giant exoplanet atmosphere

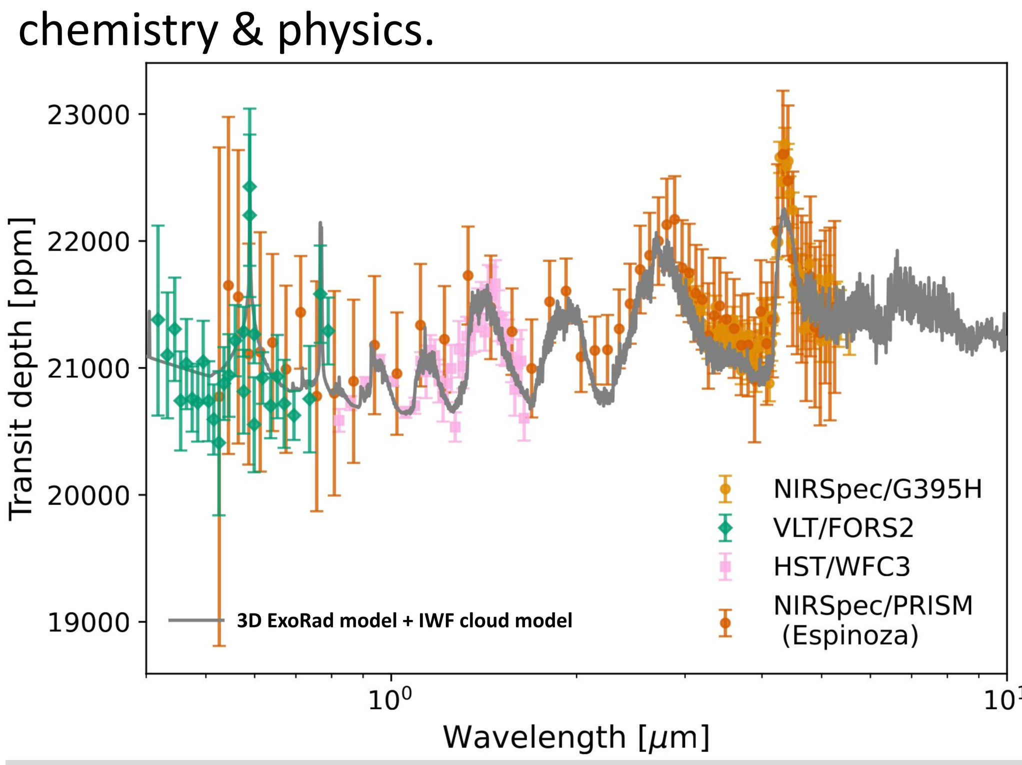
1D kinetic–photochemical model ARGO is used to explore how the vertical mixing shapes exoplanet atmospheric composition across grids of metallicity, C/O ratio, eddy diffusion coefficients (K_{zz}), and temperature, K_{zz} remains one of the least constrained inputs in atmospheric modelling, yet it strongly influences the vertical distribution of chemically active species. Photochemical products like C_2H_2 are especially sensitive, as higher K_{zz} quenches locally produced gradients. Because different molecules quench at different pressures, combining multiple species allows us to trace mixing strength of different pressure layers and infer the pressure-dependent K_{zz} profile. ***Bangera et al. 2025***).

EXOPLANET CLIMATES FROM OPTICAL TO INFRARED



How the 3D cloud coverage changes for different exoplanet climate regimes: warm (Tglobal = 800 - 1000 K), intermediately hot (1200 to 2000 K) and ultrahot (2200 - 2600 K)

The 3D AFGKM ExoRad GCM grid yielded (with the kinetic and non-equilibrium cloud model) 50 3D cloud models for three climate regimes. Clouds impact spectra by amplifying local gas temperature differences and asymmetric cloud coverage. The multi wavelength spectrum of the JWST early release science target WASP-39 b (Tglobal = 1100 K) highlights that IWF Graz transit transmission spectra yield good agreement and informs the cloud chemistry & physics.



WASP-39 b multi-instrument transmission spectrum from the optical to infrared reproduced by the 3D ExoRad model

WASP-39 b shows a dearth of iron species (Fe[s], FeS[S], Fe_2SiO_4 [s]) and dominance of silicate (Mg_2SiO_4 [s], SiO_2 [s]) species. The optical wavelength range covered with PLATO and CHEOPS is highly sensitive to average particle sizes and abundances of cloud condensation nuclei in the upper atmosphere. These findings shed light on the dynamical processes of the cloud formation processes from the top to the bottom (***Carone, Helling et al., in press***).

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