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Clouds form on the hot Saturn JWST ERO target WASP-96b

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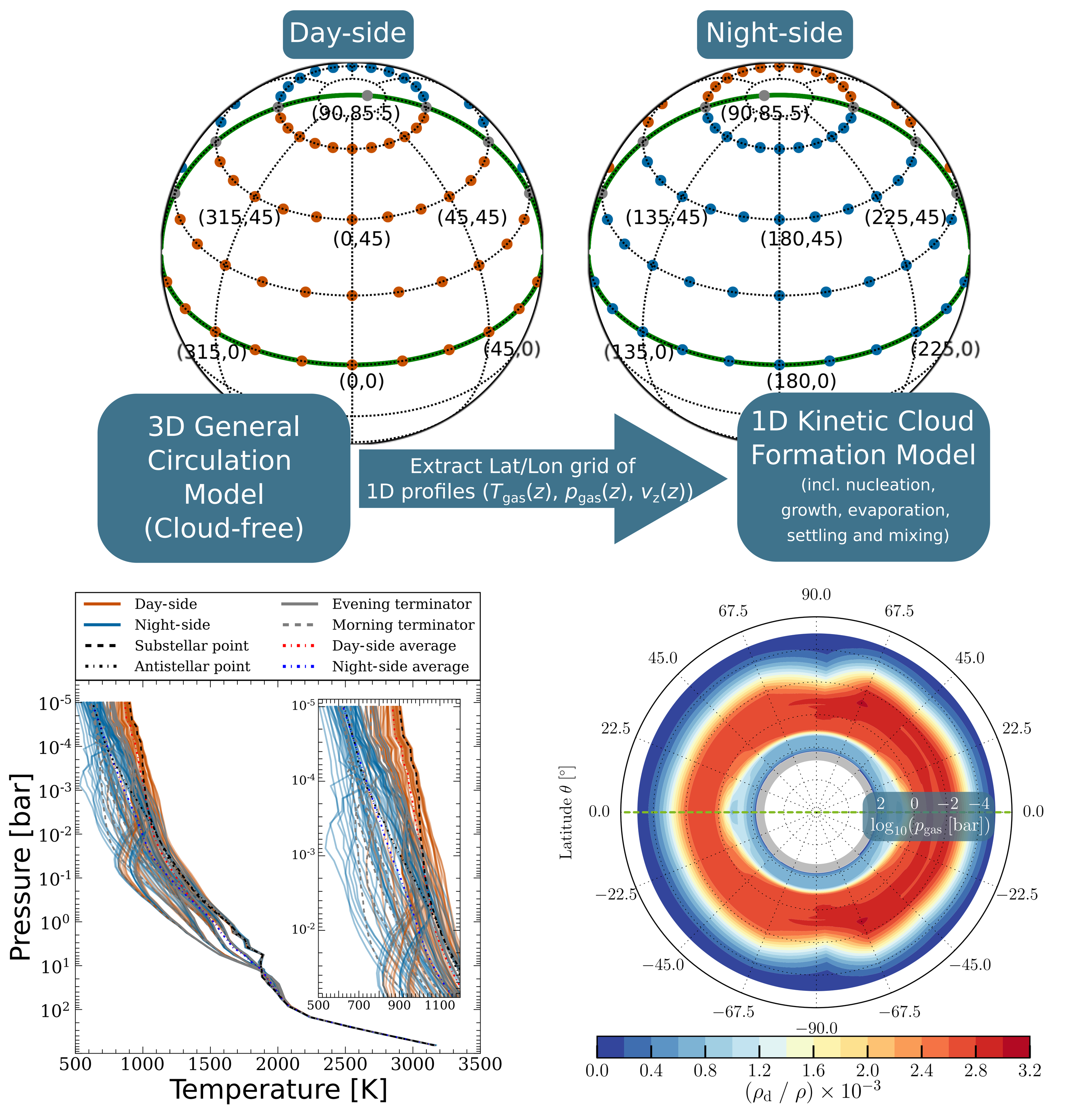
INTRODUCTION

Clouds remain a key challenge in observations of exoplanets by altering the local atmospheric composition through condensation (e.g. C/O), as well as obscuring deeper atmospheric layers. WASP-96b is a hot Saturn exoplanet, recently observed with JWST as part of Early Release Observations (Pontoppidan+ 2023). With an equilibrium temperature of $T_{\rm eq} = 1300\,{\rm K}$, WASP-96b is well within the regime of thermodynamically expected cloud formation. However, previous observations with Hubble/WFC3, Spitzer/IRAC, and VLT/FORS2 have suggested a cold but cloud-free atmosphere (Nikolov+ 2022).

Hierarchical microphysical modelling

We use 1D p-T profiles extracted from the cloud-free General Circulation Model (GCM) expeRT/MITgcm (Schneider+ 2022) as input for a kinetic cloud formation model consistently linked with gas-phase equilibrium chemistry.

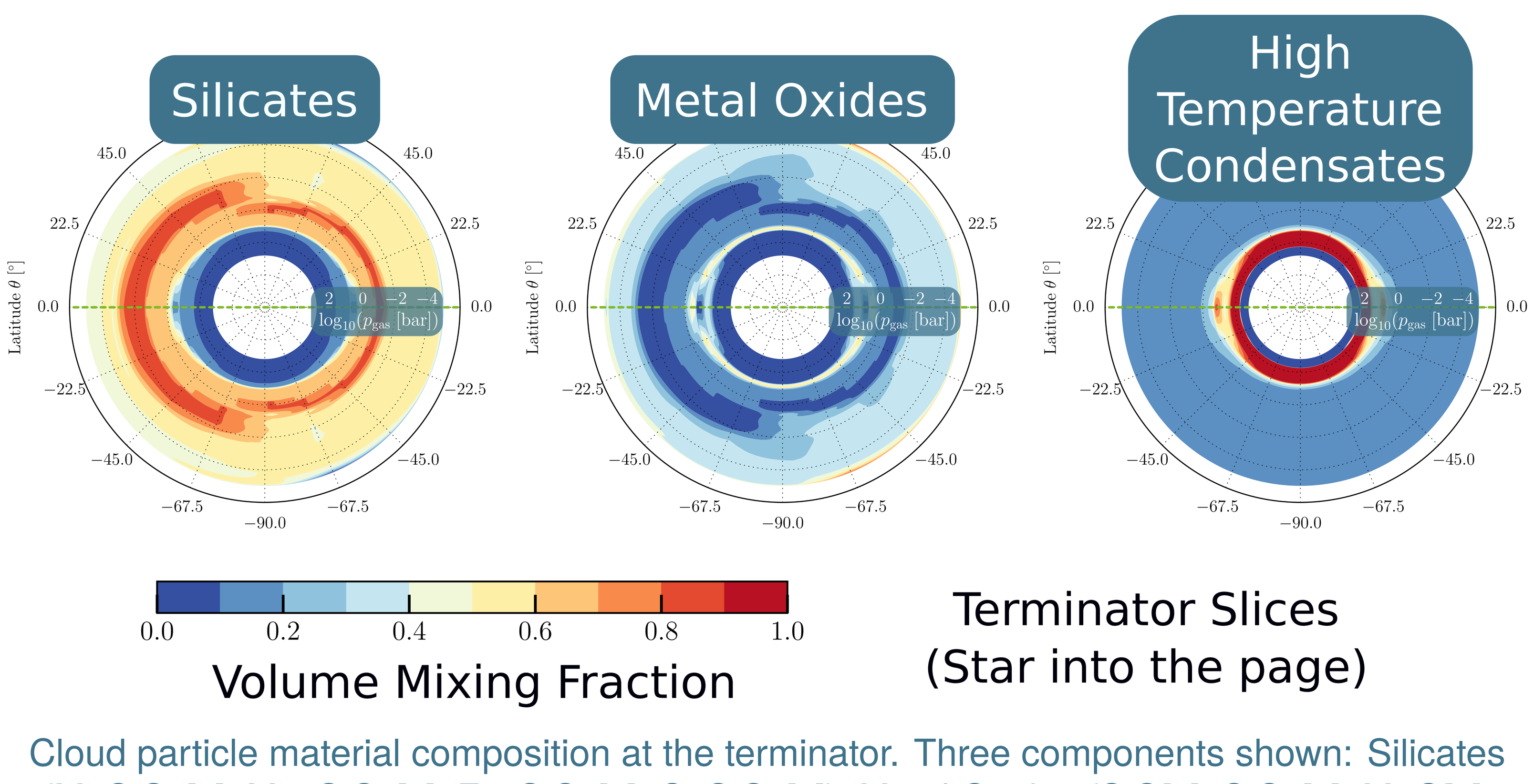


Top: 1D extracted profiles and hierarchical modelling approach summary. **Bottom Left:** 1D p-T structures from GCM. **Bottom Right:** Cloud particle mass load at the terminator limb, evening terminator on the left, morning terminator on the right.

GCM p-T profiles generally decrease monotonically with height, $T < 1000\,{\rm K}$ below $1\,{\rm mbar}$. No dramatic difference between day-side and night-side. Cloud formation at the terminators is largely uniform (peaks at around $10\,{\rm mbar}$), with an increase on the morning terminator compared with the evening terminator.

Terminator cloud properties and optical depth

Cloud particles in the atmosphere of WASP-96b are highly mixed; silicates dominate the composition, but there is also a significant contribution of metal oxides. Salts do not condense in any meaningful amount, and high temperature condensates are only significant at pressure $> 1\,{\rm bar}$.



Cloud particle material composition at the terminator. Three components shown: 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], Fe_2O_3[s]), and High Temperature Condensates (TiO_2[s], Fe[s], FeS[s], Al_2O_3[s], $CaTiO_3$[s]). Salts (KCl[s], NaCl[s]) not shown as < 0.1 at all pressures.

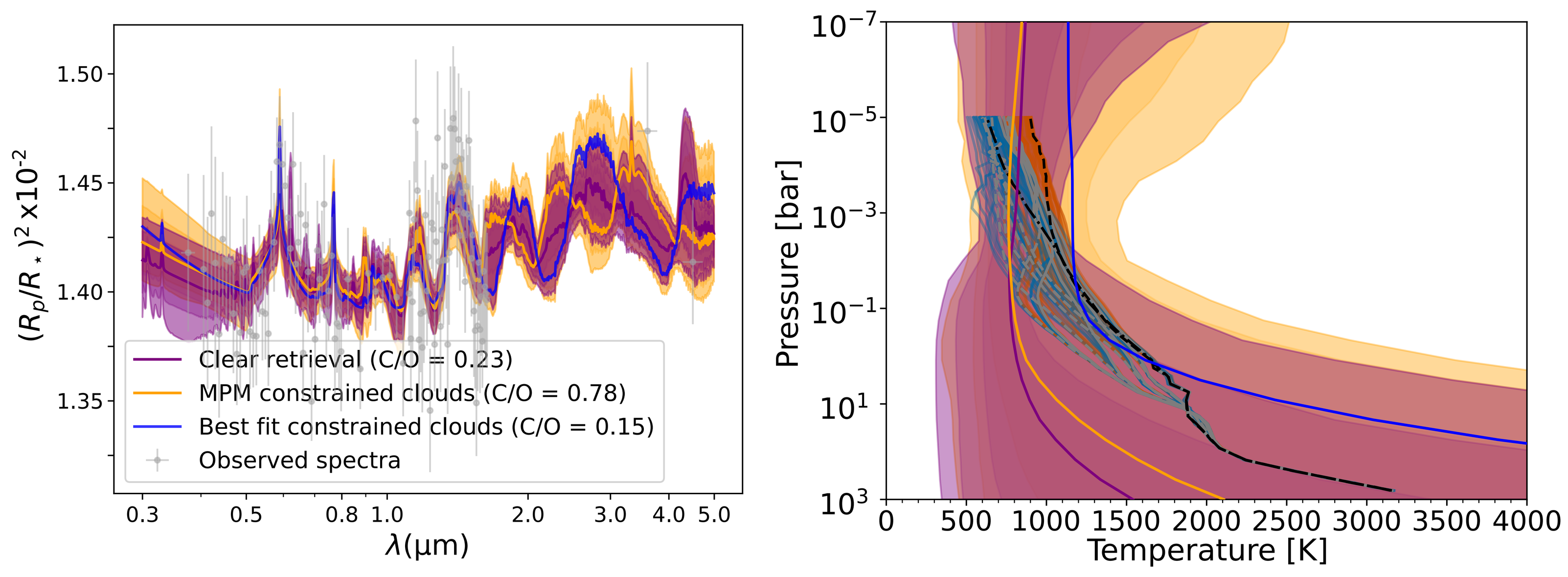
Retrieval of pre-JWST spectra with ARCiS

We apply the Bayesian retrieval code ARCiS (Min+ 2020) to the Nikolov+ 2022 spectrum. This includes an 'intermediate' complexity cloud model: with equilibrium condensation, nucleation parameterised by a column-integrated nucleation rate $\log_{10}\dot{\Sigma}\,[{\rm g\,cm^{-2}\,s^{-1}}]$, and transport parameterised by $K_{zz}\,[{\rm cm^2\,s^{-1}}]$ (Ormel & Min 2019).

Name	Description
Parameters included for both cloud formation and clear retrievals	
$R_{\rm p}$	Planet radius
$\log_{10}(g_{\rm p})$	Base-10 logarithm of the planet surface gravity $^{(b)}$
C/O	Atmospheric carbon-to-oxygen ratio
N/O	Atmospheric nitrogen-to-oxygen ratio
Si/O	Atmospheric silicon-to-oxygen ratio
[Z]	Atmospheric metallicity (global)
$\log_{10}(\gamma)$	Ratio of visible to IR opacity
$f_{\rm irr}$	Irradiation parameter
$\log_{10}(\kappa_{\rm IR})$	Infrared opacity
$T_{\rm int}$	Temperature at an optical depth $\tau = \frac{2}{3}$ as caused by internal heat from the planet
Parameters included in cloud formation retrieval only	
K_{zz}	Cloud diffusion coefficient
$\log_{10}\dot{\Sigma}$	Nucleation rate

Table of parameters for clear retrieval (**Top**) and additional cloud parameters (**Bottom**). Details in: Min+ 2020, Chubb & Min 2022

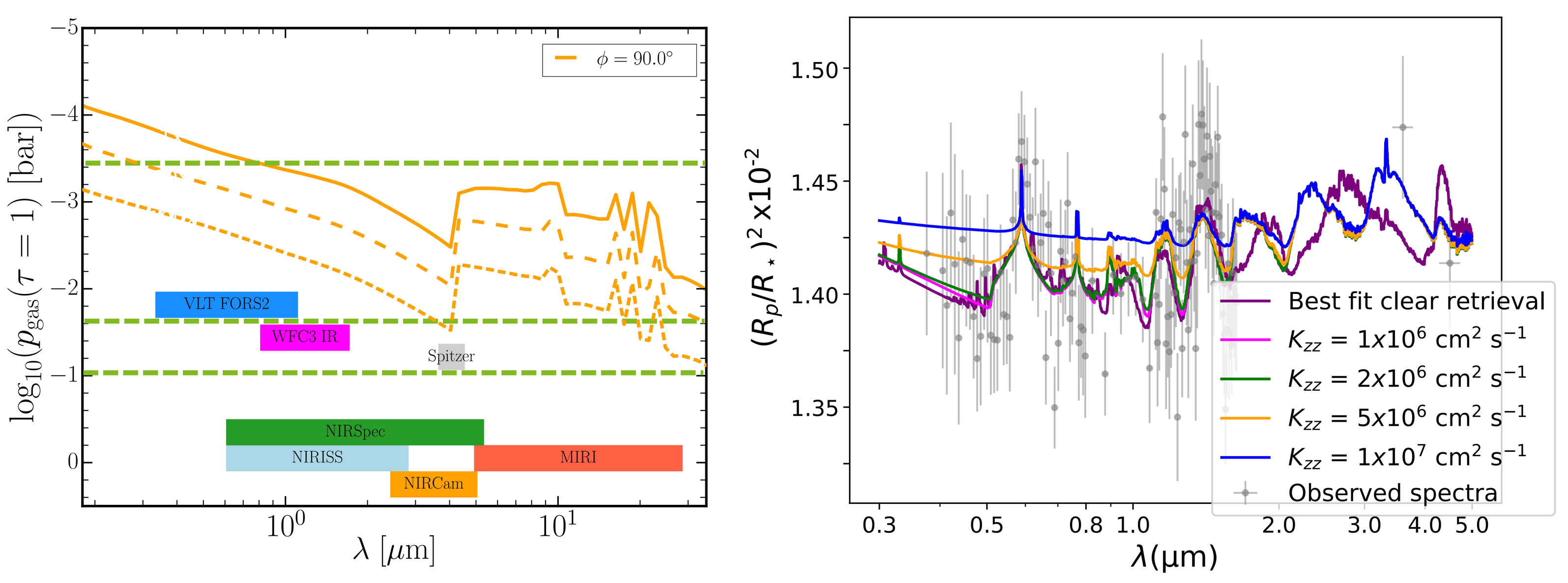
Both clear and cloudy retrievals provide good fits to the data (reduced-$\chi^2 = 1.08$ and 1.09 respectively). Two cloudy solutions fit the data with differing C/O ratios (more details: Samra+ 2023). The inferred p-T profiles are broadly in agreement with Nikolov+ 2022 and with the GCM cloud-free 1D profiles.



Left: Spectra for three retrieval solutions: clear, cloudy best fit, and cloudy Most-Probable Model (MPM). **Right:** p-T profiles from retrieval solutions, alongside GCM 1D profiles.

Mixing reduced in both retrieval and modelling

The retrievals parametrise mixing by K_{zz}, and the microphysical model parametrises mixing with a timescale ($\tau_{\rm mix} = H_{\rm p}/\langle v_z \rangle$). In both cases, reduced mixing is needed to bring the cloud deck deeper into the atmosphere, where the Na line can be pressure broadened ($\sim 10\,{\rm mbar}$ from Nikolov+ 2022).



Left: Optical depth of clouds for evening terminator with increased mixing timescale. **Right:** Spectra for best-fit clear retrieval as well as cloudy model with altered K_{zz}.

SUMMARY

- Microphysical modelling suggests that WASP-96b does have a cloudy atmosphere.
- ARCiS retrievals applied to HST, Spitzer, and VLT data shows that multiple cloudy solutions do reproduce the observed spectra. Thus the retrieved solutions may not be unique, requiring more physical input.
- WASP-96b could only be cloud-free in the region probed by observations in the case of extremely low mixing efficiency, or if a temperature inversion confines the clouds to higher pressures.

Find the paper here:

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