KU LEUVEN | TU GRAZ | OEAW IWF

UNLOCKING THE COMPLEXITY OF 3D EXOPLANET ATMOSPHERES: A COMBINED MODELING APPROACH AND OBSERVATIONAL IMPLICATIONS

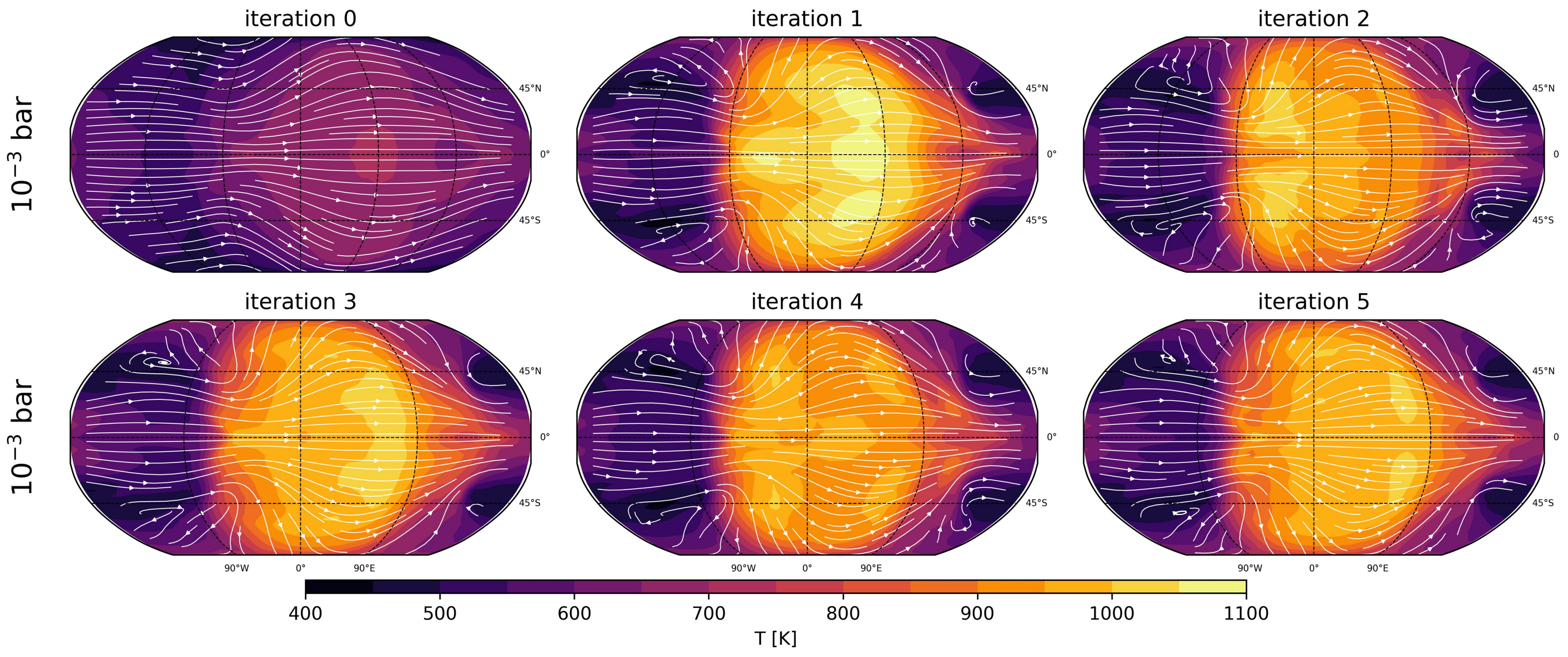
S. Kiefer[1,2,3], N. Bach-Møller[2,3,4], D. Samra[2], D. A. Lewis[2,3], A. D. Schneider[1,4], F. Amadio[4,1], H. Lecoq-Molinos[2,3,1], L. Carone[2], L. Decin[1], U. G. Jørgensen[4], and Ch. Helling[2,3]

Take Home Message

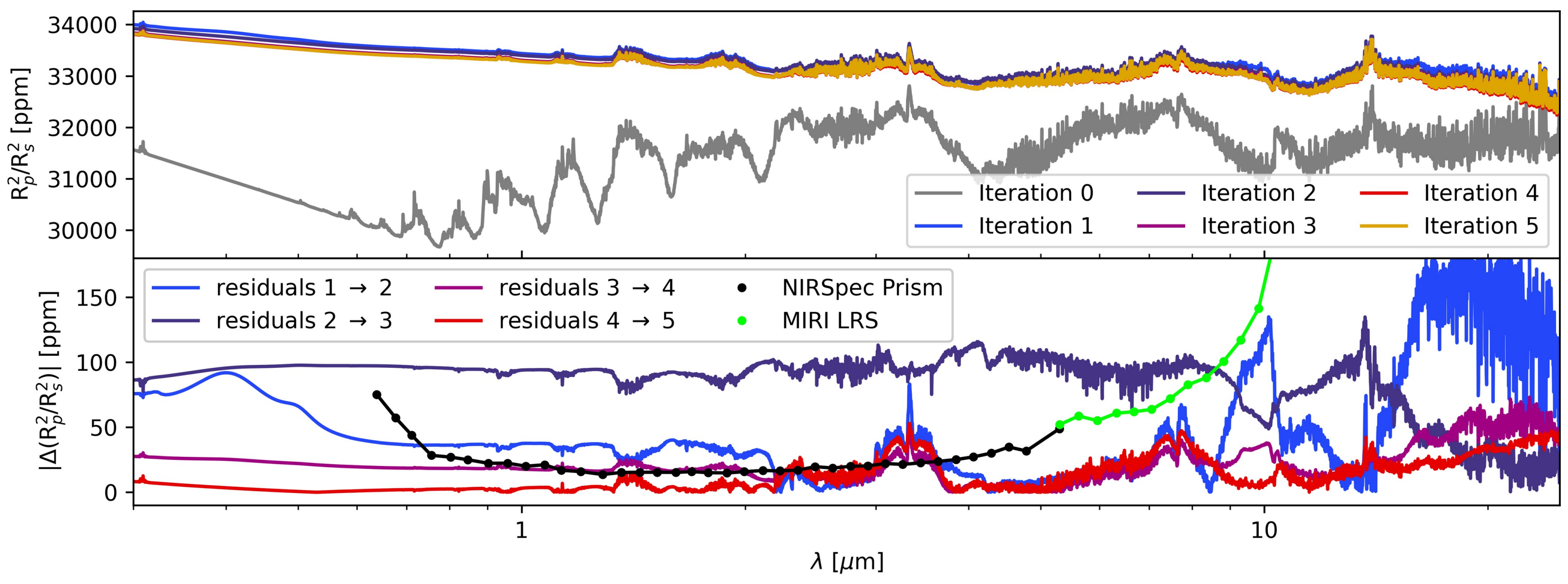
- ➔ **Warm Saturns around M-dwarfs, like HATS-6b, are ideal targets to study the atmospheric structure of cloudy exoplanets.**
- ➔ **Our iterative model allows to efficiently combine detailed micro-physical cloud models with GCMs.**
- ➔ **HATS-6b has a global cloud coverage which causes a temperature inversion. Observations have the potential to detect cloud and CH_4 features.**

ITERATIVE CLOUD-CLIMATE MODEL

The aim of this work is to explore the combined atmospheric and micro-physical cloud structure, and the kinetic gas-phase chemistry of warm Saturn-like exoplanets in the irradiation field of an M-dwarf. To achieve this, we **iteratively combine** the 3D General Circulation Model (GCM) **expeRT/MITgcm** (Carone et al. 2020; Schneider et al. 2022) and a detailed, **micro-physical cloud model** (Helling et al. 2006). Each iteration starts with a GCM run of 2000 simulation days. The output is used to calculate the cloud structure which is then used as static opacity source for the next GCM run. Iteration 0 (It. 0) is cloudless and each following iteration includes cloud particle opacity. The isobaric slices for each iteration can be seen below.



Between the cloudless (It. 0) and the cloudy (It. 1+) GCM runs, large differences in the temperature and wind structure can be seen. However, already between It. 1 and It. 2, the general atmospheric structure remains the same. To test if the changes have an observable effect, we produce the transmission spectra for all iterations using petitRADTRANS (Mollière et al. 2019). We calculate the absolute differences between subsequent iterations and compare them to the spectral precision of NIRSpec Prism and MIRI LRS for 10 Transits:



The transit depth differences between It. 3 to 4 and between It. 4 to 5 are generally **below the spectral precision of JWST** and are unlikely to be observable. Therefore, we stop our iterative model after It. 5 and use It. 5 to analyse the atmospheric structure of HATS-6b.

THE CLOUDY CLIMATE OF HATS-6B

HATS-6 b

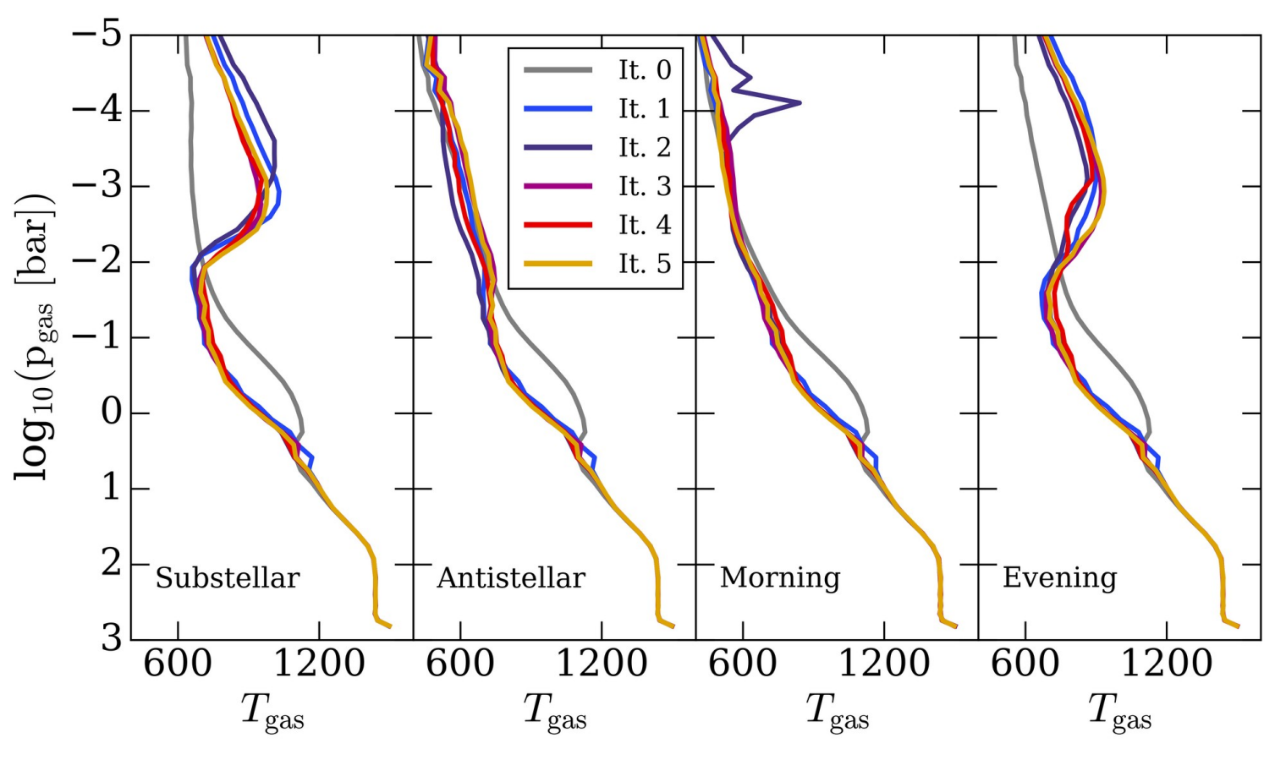
Star:
$0.57\ M_\odot$
$0.57\ R_\odot$
3724 K
M-dwarf

Planet:
$0.319\ M_J$
0.998 RJ
700 K ($T_{equilibrium}$)
Warm Saturn

HATS-6b (Hartman et al. 2015) is a transiting warm Saturn orbiting an **M-dwarf host star.** The existance of such planets questions formation models that predict that only more massive stars have a protoplanetary disk with enough material to form gas-giants. The higher magnetic activity of M-dwarfs is expected to expose exoplanets around these types of stars to higher amounts of **stellar energetic particles (SEPs).**

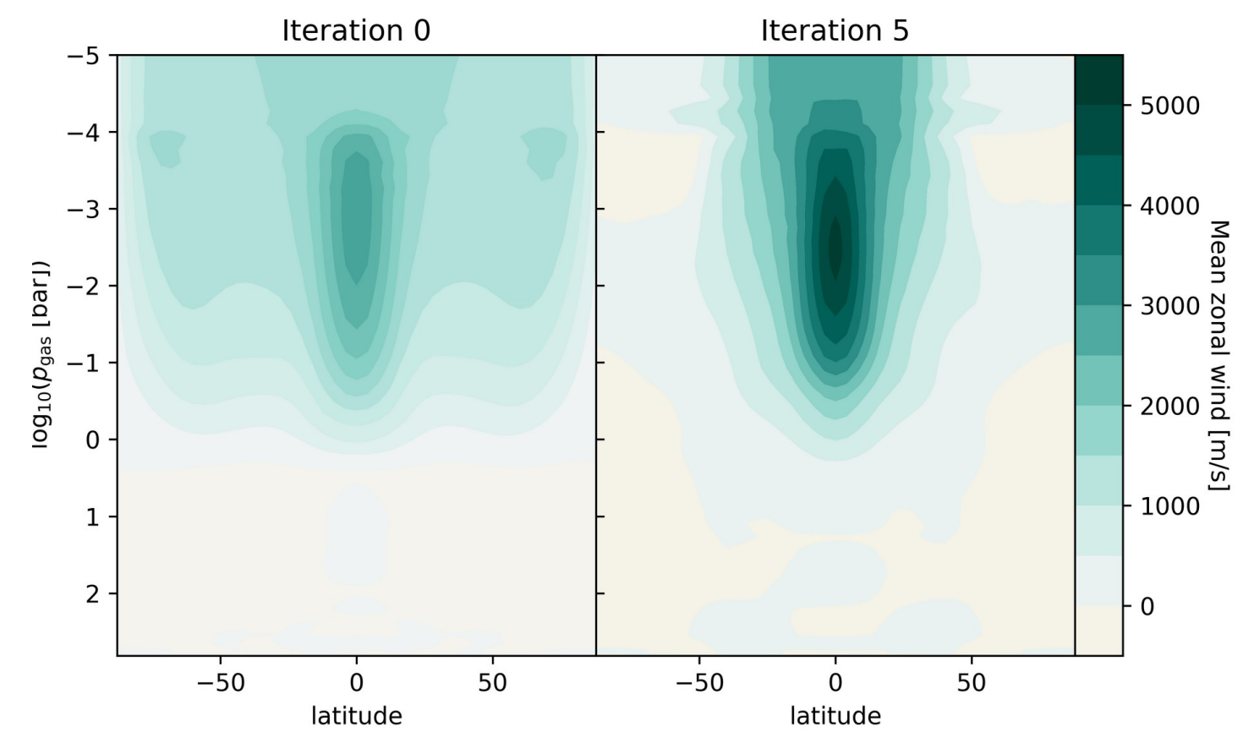
TEMPERATURE

On the day-side of HATS-6b, cloud particles cause a **temperature inversion** in the upper atmosphere and an **anti-greenhouse effect** at higher pressures that extends to the night-side.



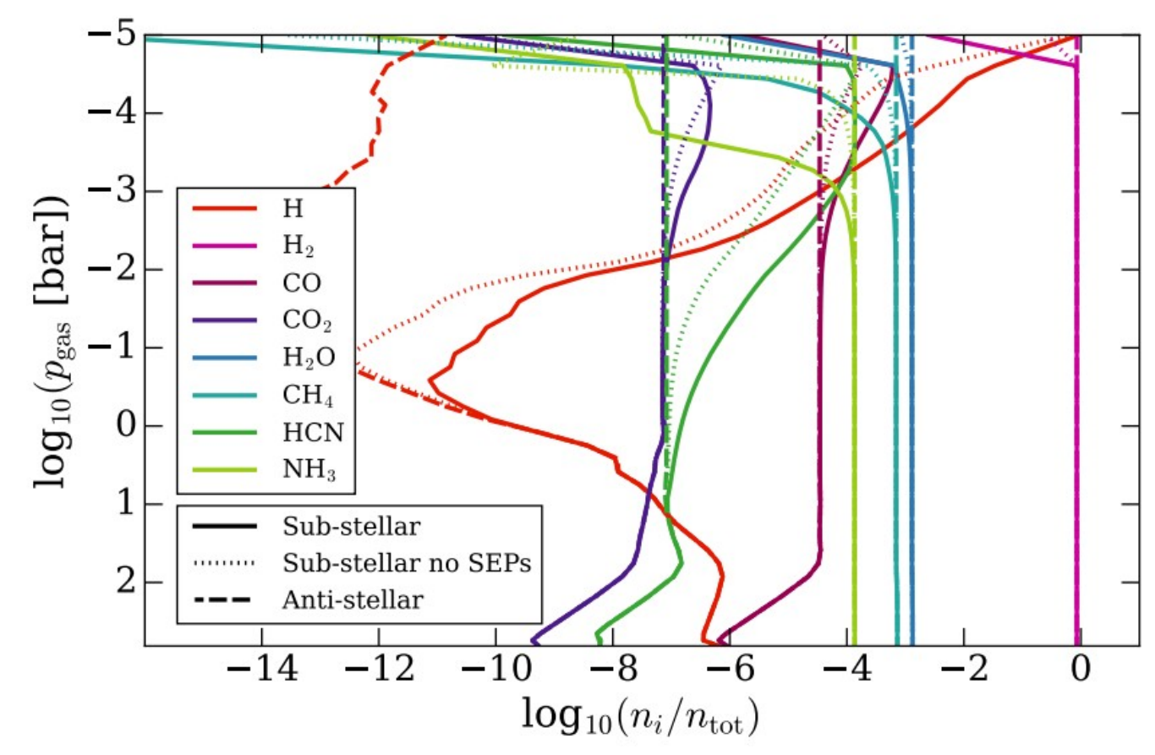
WINDS

The higher temperatures in the upper atmosphere lead to a **stronger and narrower wind jet**. This jet stream transports the temperature inversion from the day-side into the evening terminator.



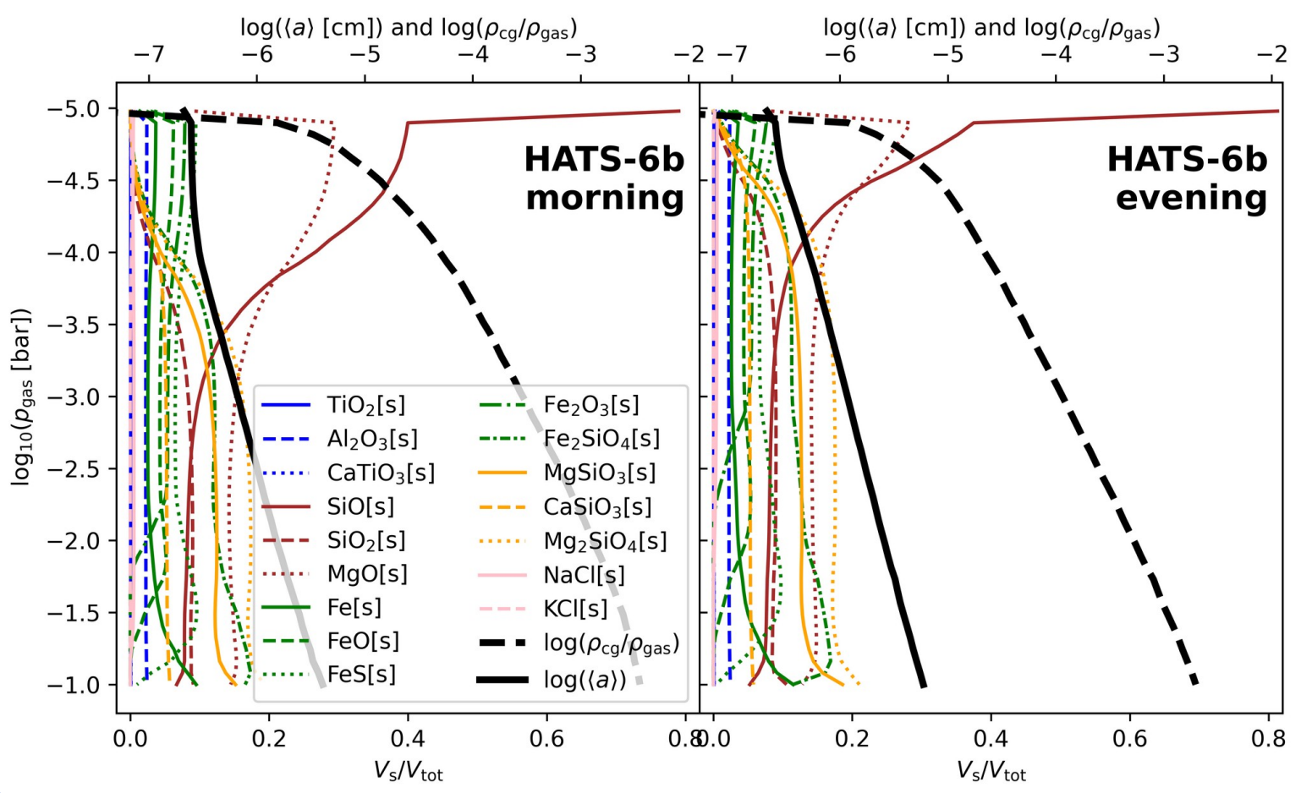
CHEMISTRY

The chemical structure of HATS-6b is affected by quenching, photochemistry and SEPs. A closer look at SEPs reveals that they **reduce the abundance of CH_4** on the day-side.



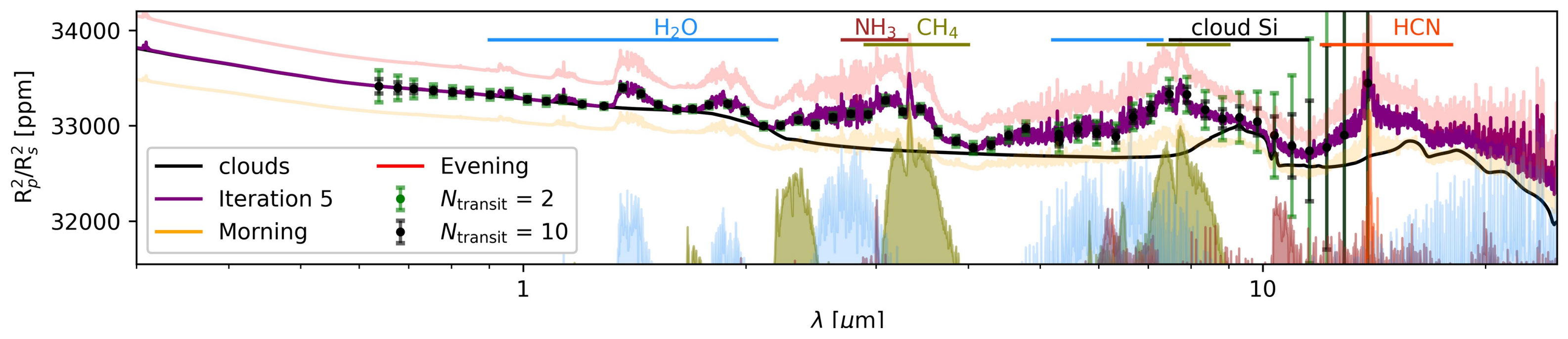
CLOUDS

HATS-6b has a **global but not uniform** cloud coverage. The cloud particles are highly mixed with **silicates** being the dominant cloud particle material followed by iron-bearing species.



SPECTRA

The spectra of HATS-6b has **observable gas-phase** (CH4, H2O) and **cloud particle features** which are asymmetric between the limbs. The high transit depths are the result of a large planet around a small star which makes HATS-6b an ideal target.



Acknowledgments:
S.K. N.BM., A.D.S, F.A, H.LM., L.C., Ch.H., L.D., U.G.J. acknowledge funding from the European Union H2020-MSCA-ITN-2019 under grant agreement no. 860470 (CHAMELEON). D.A.L., D.S. acknowledge financial support from the Austrian Academy of Sciences. We acknowledged the computation support at the IWF Graz and CPH. LD acknowledges support from the KU Leuven IDN grant IDN/19/028 grant Escher. U.G.J. acknowledges funding from the Novo Nordisk Foundation Interdisciplinary Synergy Programme grant no. NNF19OC0057374.

Affiliations:
[1] Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
[2] Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria
[3] Institute for Theoretical Physics and Computational Physics, TU Graz, Petersgasse 16, Graz, Austria
[4] Centre for ExoLife Sciences, Niels Bohr Institute, Oster Voldgade 5, 1350 Copenhagen, Denmark

References:
Carone L., Baeyens R., et al. 2020, MNRAS 496 3582
Hartman J.D., Bayliss D., et al. 2015, ApJ 149 5 166
Helling Ch. & Woitke P., 2006, A&A 455 325-338
Mollière P., Wardenier J.P., et al. 2019, A&A 627 A67
Schneider A.D., Carone L., et al. 2022, A&A 664 A56

2024

WEBSITE: KIEFERSV.GITHUB.IO | EMAIL: SVEN.KIEFER@KULEUVEN.BE | NEED A BREAK? BE A CLOUD!