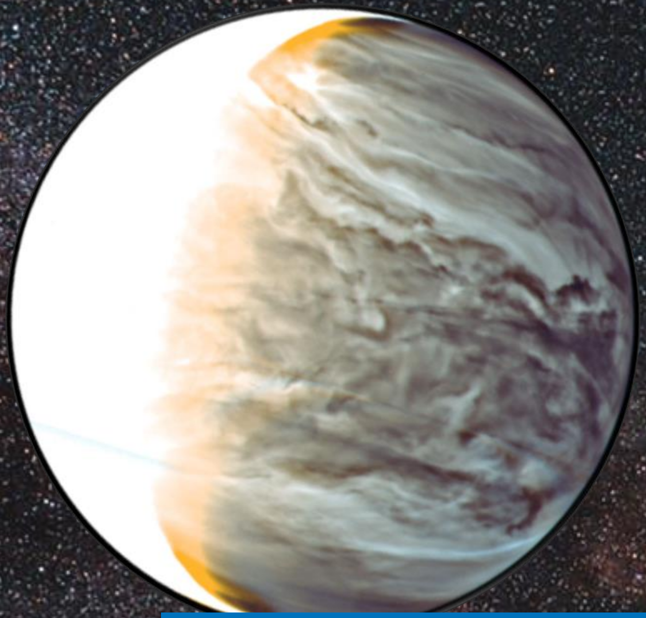

3D Climate Modelling of TRAPPIST-1 c with a Venus-like atmosphere

Large-scale circulation and observational prospects

This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

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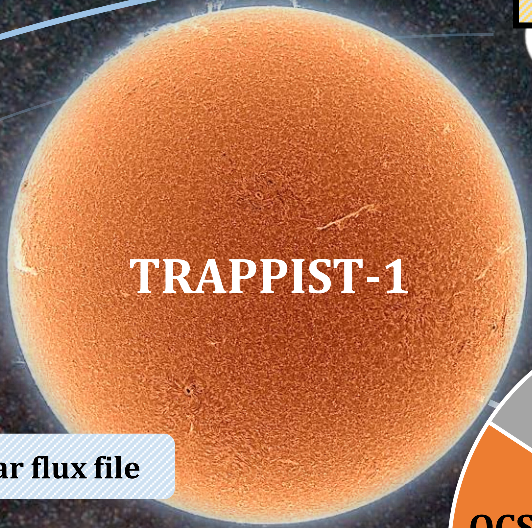
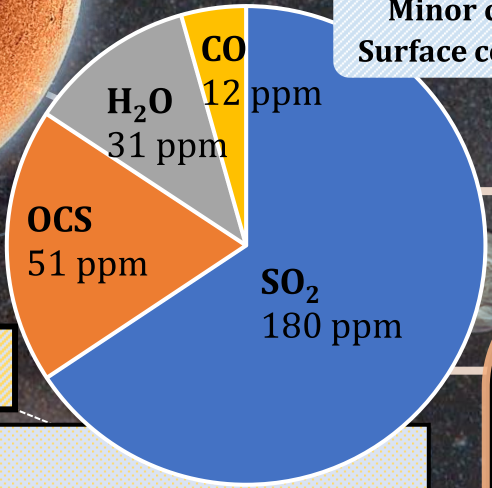
Planetary Parameters used in the simulation of TRAPPIST-1 c



Stellar flux file

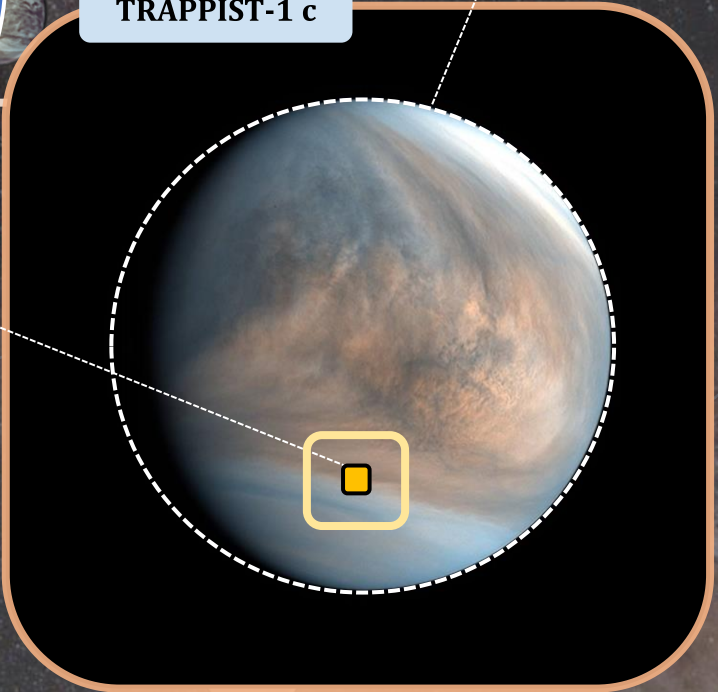
Minor components
Surface concentrations



Geophysical Parameters

- Radius, R = 6995 *km*
- Surface gravity, g = 10.65 $m\ s^{-2}$
- Synchronous rotator
- Solid-body rotation period, P = 209 000 *s*
- Solid-body rotation rate, $\Omega = 3 \times 10^{-5}\ rad\ s^{-1}$

TRAPPIST-1 c



Atmospheric Parameters

- Carbon dioxide dominated atmosphere (99.96%)
- Surface pressure, p = 92 *bar*
- 50 atmospheric layers (surface to p ~ 5 Pa)
- Radiatively active global Venus-like clouds (sulphuric acid) following Haus et al., 2013
- No photochemistry

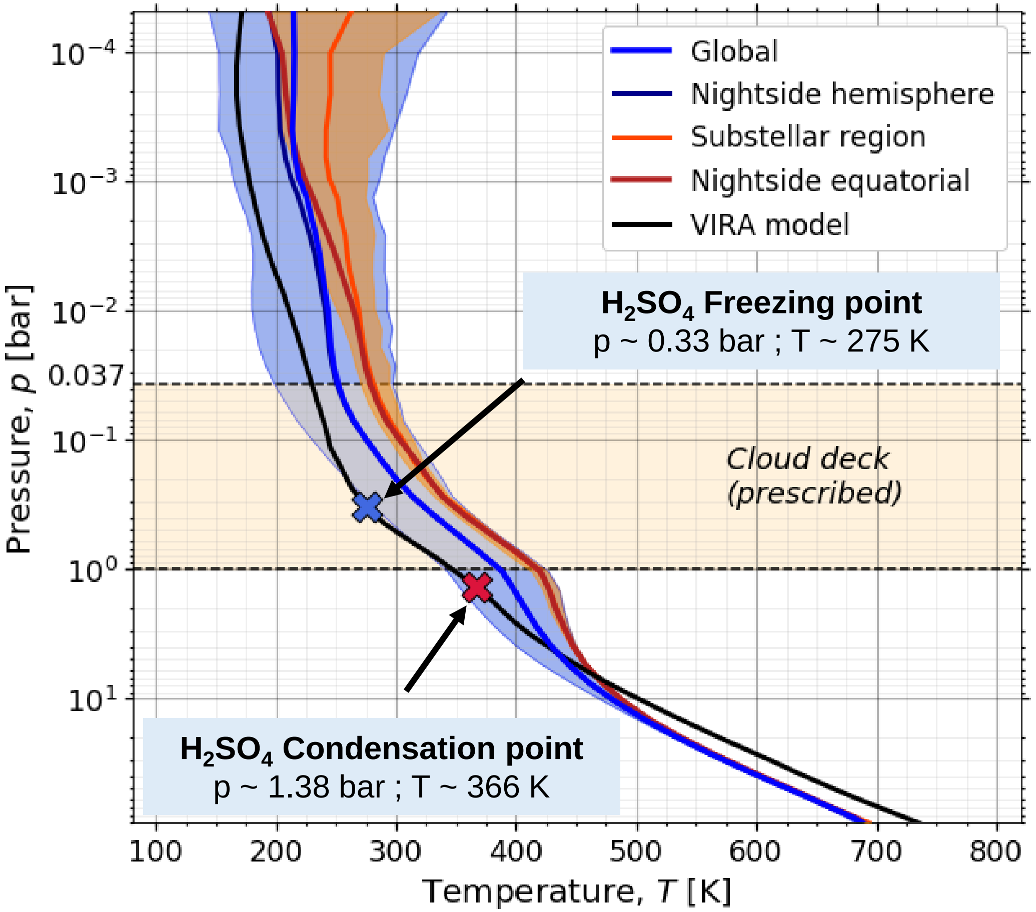
Orbital Parameters

- Semimajor axis, a = 0.0158 *AU*
- Orbital period, T = 2.42 *days*
- Stellar flux at TOA, S = 3015 $W\ m^{-2}$
- No obliquity and eccentricity

This is a representative scheme. We are assuming that TRAPPIST-1 c has a Venus-like atmosphere.

Data in blue is taken from Agol et al., 2021

Thermal structure

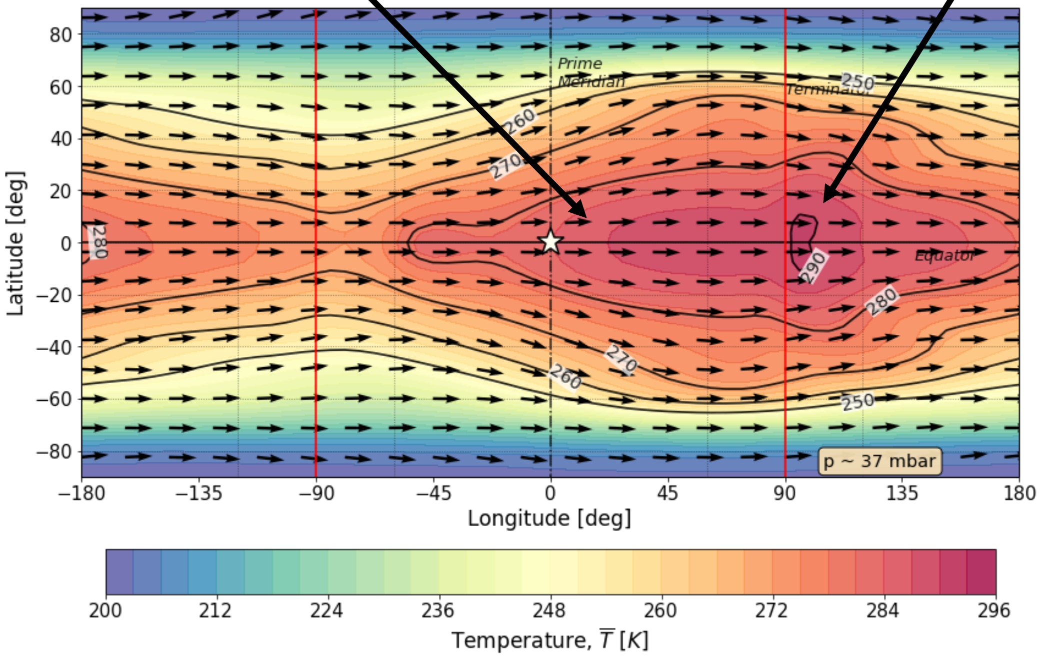


H_2SO_4 Freezing point
p ~ 0.33 bar ; T ~ 275 K

H_2SO_4 Condensation point
p ~ 1.38 bar ; T ~ 366 K

Chevron-like pattern

Hotspot eastward shift



- An overall warmer TRAPPIST-1 c atmosphere compared to that of Venus
- A warmer nightside equatorial region suggesting an efficient heat redistribution throughout the atmosphere

Large-scale circulation

Zonal Circulation

Equatorial zonal superrotation jet
High-latitudes jets

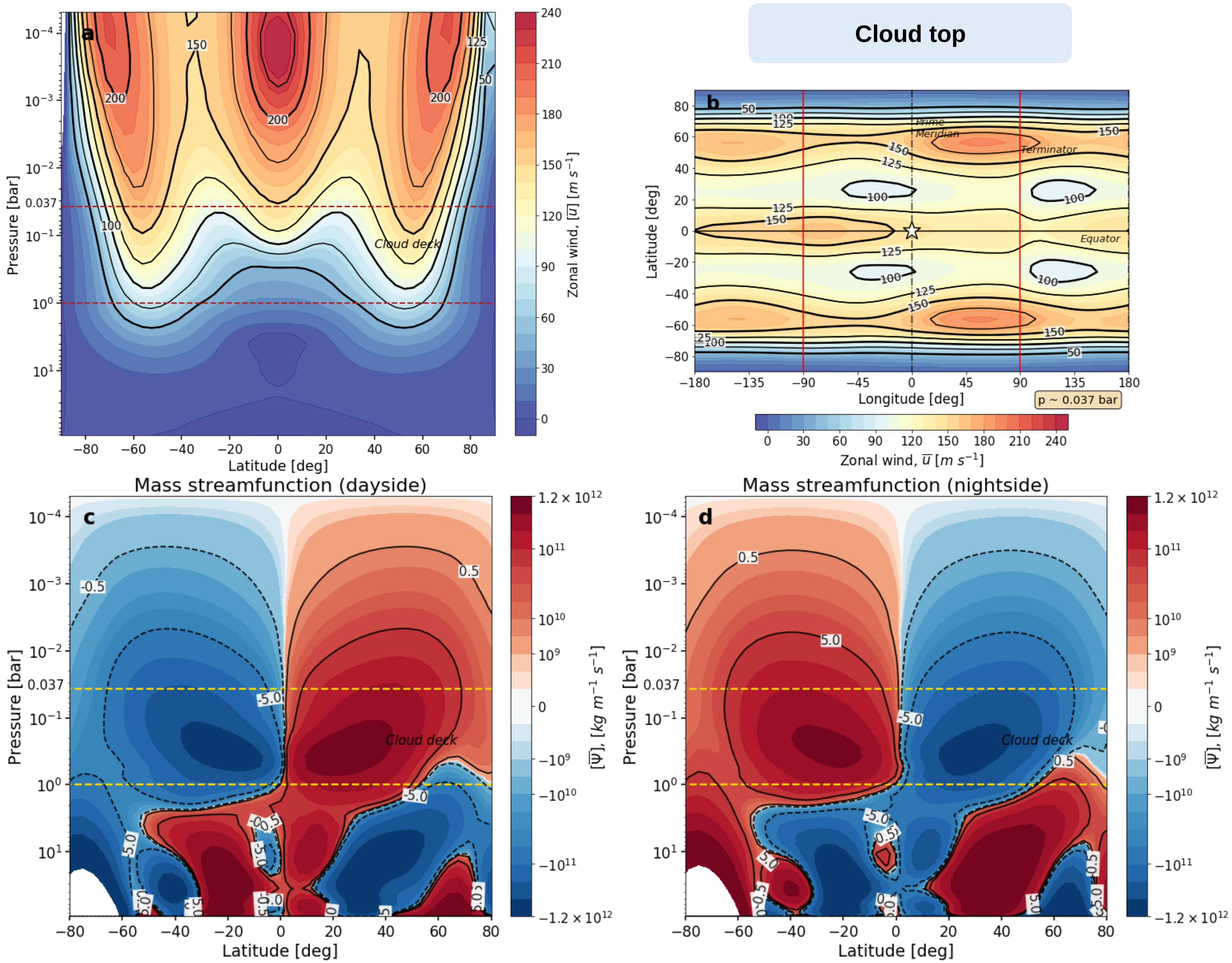
Meridional Circulation

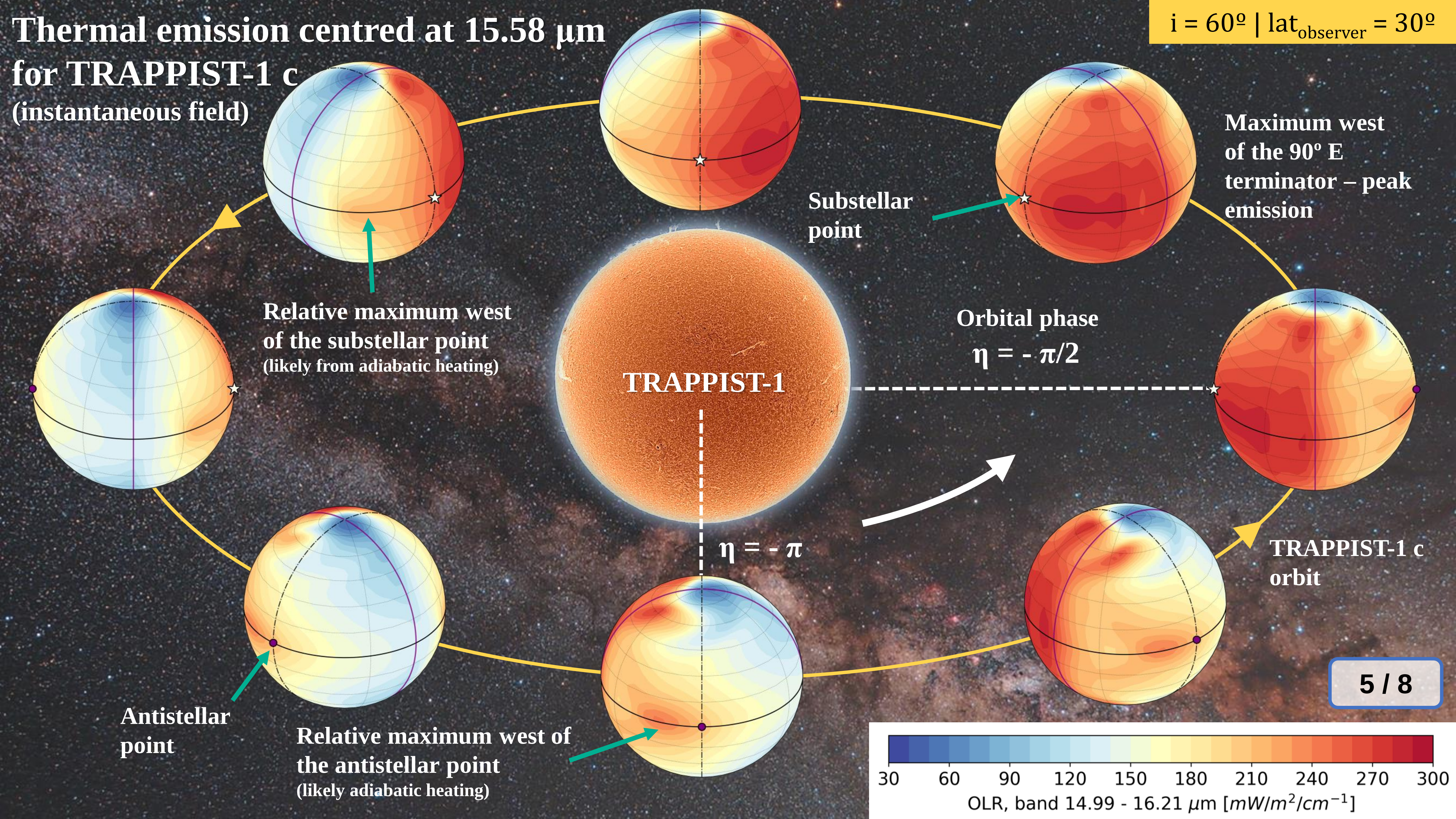
Dayside: poleward circulation
Nightside: equatorward circulation

Large-scale circulation:
One large cell per hemisphere

Each cell will cross the polar region

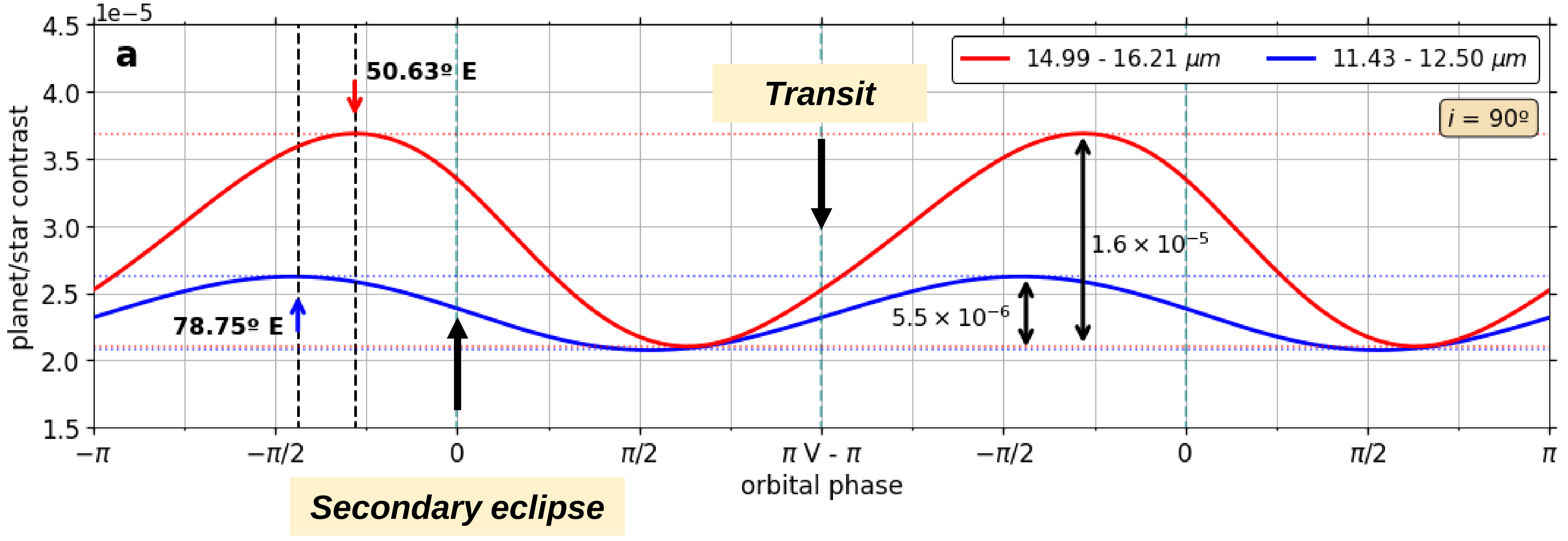
Strong heat redistribution




Thermal emission centred at 15.58 μm
for TRAPPIST-1 c
(instantaneous field)
i = 60º | lat$_{observer}$ = 30º
Maximum west
of the 90º E
terminator – peak
emission
Substellar
point
Relative maximum west
of the substellar point
(likely from adiabatic heating)
TRAPPIST-1
Orbital phase
η = - π/2
η = - π
TRAPPIST-1 c
orbit
5 / 8
Antistellar
point
Relative maximum west of
the antistellar point
(likely adiabatic heating)
30
60
90
120
150
180
210
240
270
300
OLR, band 14.99 - 16.21 μm [mW/m^2/cm^{-1}]

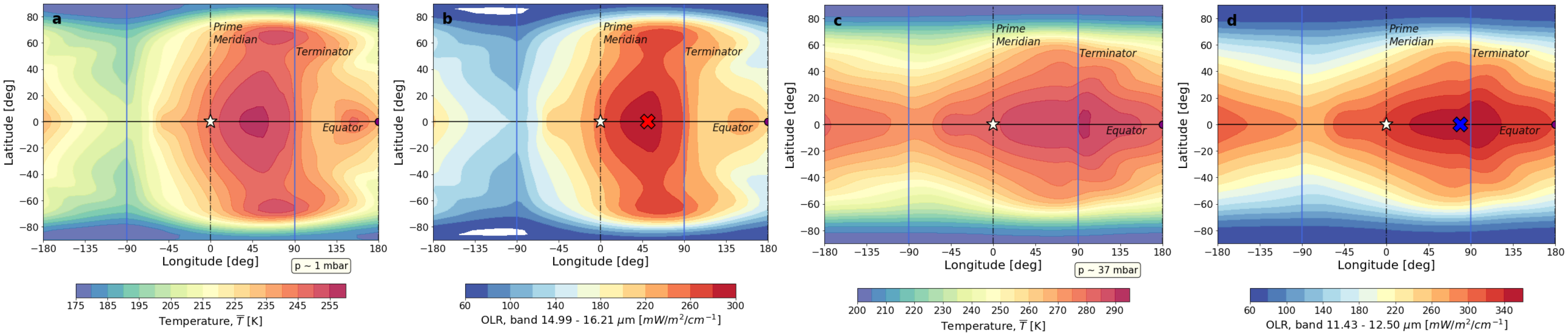
Thermal phase curves, OLR and Temperature fields

Sounding different atmosphere levels

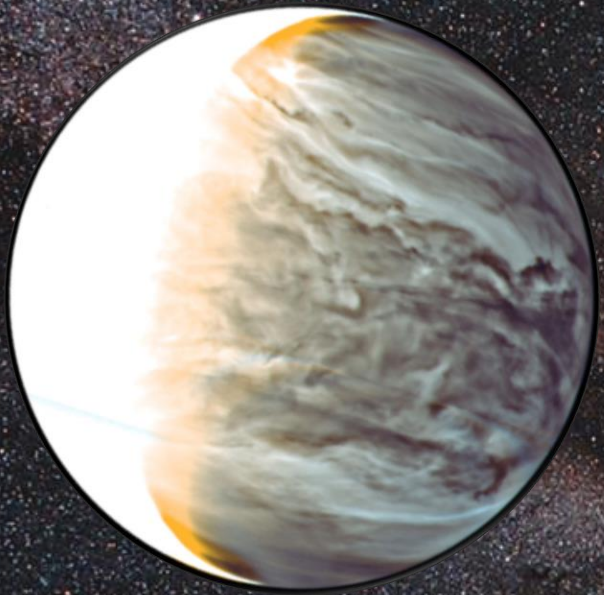


Mesosphere p ~ 1 mbar

Cloud tops, p ~ 37 mbar

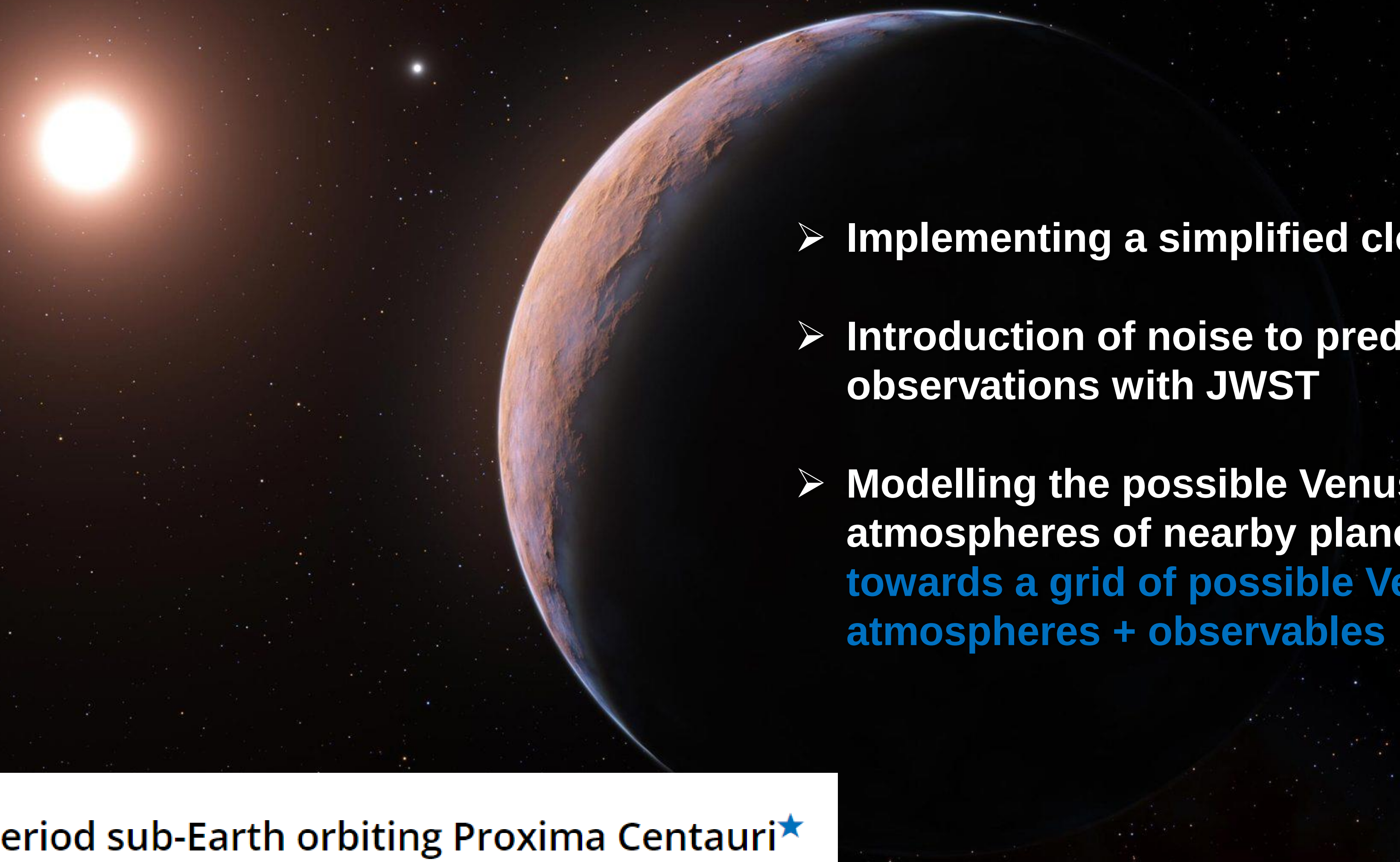


Take-home messages



- Temperature field at the cloud tops (p ~ 37 mbar): **chevron-like pattern** and **eastward shift** of the hotspot
- Day-night heat redistribution: **three zonal jets** (equatorial superrotation + high-latitudes) and meridional circulation (**two large cells**, one per hemisphere and crossing the pole)
- Different spectral bands will sound different atmospheric layer:
  - Carbon dioxide absorption bands: **Mesosphere p ~ 1 mbar**
  - *Continuum* bands: **Cloud tops p ~ 37 mbar**
- Contrast values of emission phase curves might enable the exploration of a possible Venus-like atmosphere around TRAPPIST-1 c with JWST and other instruments

Future work



- Implementing a simplified cloud model
- Introduction of noise to predict future observations with JWST
- Modelling the possible Venus-like atmospheres of nearby planets: towards a grid of possible Venus-like atmospheres + observables

A&A 658, A115 (2022)

A candidate short-period sub-Earth orbiting Proxima Centauri★

Credit: ESO/ L. Calçada

Additional slides

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Project Overview and Research Questions

Objectives

(1) Characterisation of the **large-scale atmospheric circulation** of TRAPPIST-1 c with a Venus-like atmosphere.

(2) Production of **synthetic observables** (reflection and emission phase curves) of TRAPPIST-1 c.

- Venus-like exoplanets orbiting M-dwarf stars

LMD Generic Global Climate Model

Planetary Parameters

- Planetary radius
- Gravity
- Surface atmospheric pressure
- Solid-body rotation rate
- Stellar flux at TOA

Synthetic Observables

- OLR
- Reflected light

Large-scale atmospheric circulation + Synthetic phase curves

e.g., superrotation, planetary waves (Kelvin and Rossby waves) …

Reflection and emission

Method: Setting a Venus-like atmosphere

Table 1. Selected atmospheric composition (Venus data: Taylor et al., 2018)

Chemical species	Simulations	Venus
Main Components		
Carbon dioxide (CO_2)	99.96% *	96%
Nitrogen (N_2)	-	3.5%
Minor Components		
Sulphur dioxide, (SO_2)	180 ppm	150 ppm
Carbonyl sulfide, (OCS)	51.0 ppm	4 ppm
Water vapour, (H_2O)	31.1 ppm	30 ppm
Carbon monoxide, (CO)	12.0 ppm	40 ppm

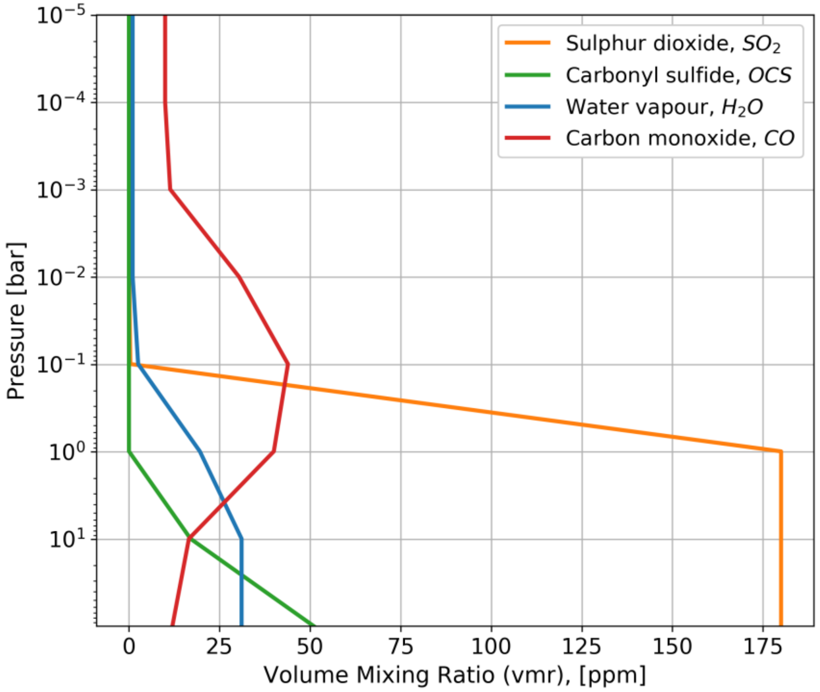


Table 2. Aerosol parameterisation

Aerosol	Mode 1	Mode 2	Mode 2p	Mode 3	“unknown” UV
Effective radius, R_{eff} (μm)	0.49	1.23	1.56	4.25	0.50
Effective variance, ν_{eff}	0.210	0.067	0.044	0.062	0.100
Top pressure, p_t (bar)	0.1	0.1	0.23	0.4	0.037
Base pressure, p_b (bar)	1	0.11	1	1	0.33

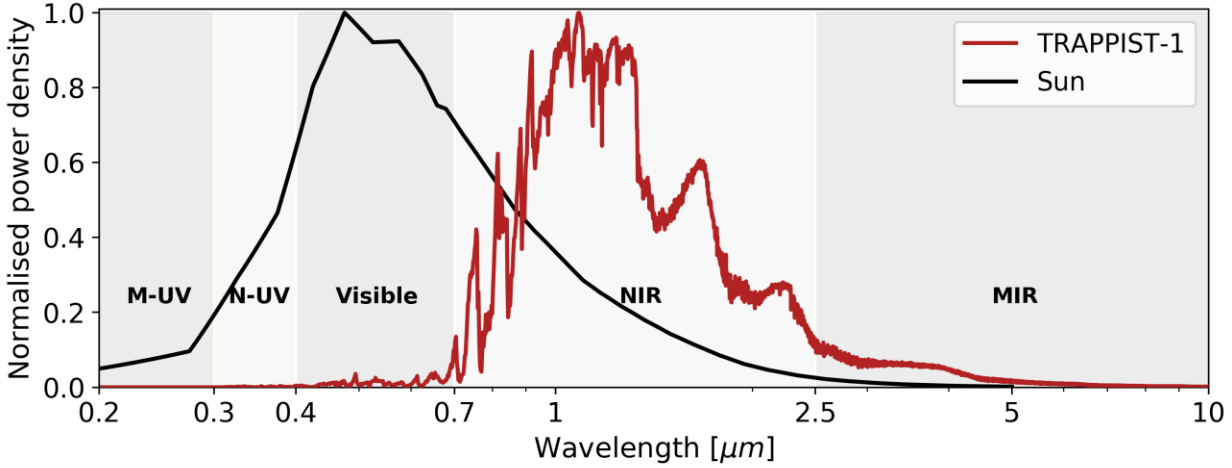
- Surface atmospheric pressure: 92-bar
- Radiatively active Venus clouds (sulphur dioxide aerosols + UV absorber) parametrised according to Haus et al., 2013
- **50** atmospheric layers (surface to 5 Pa)
- **No photochemistry!**

TRAPPIST-1 c as a synchronous rotator

Table 3. Orbital and Solid-body parameters

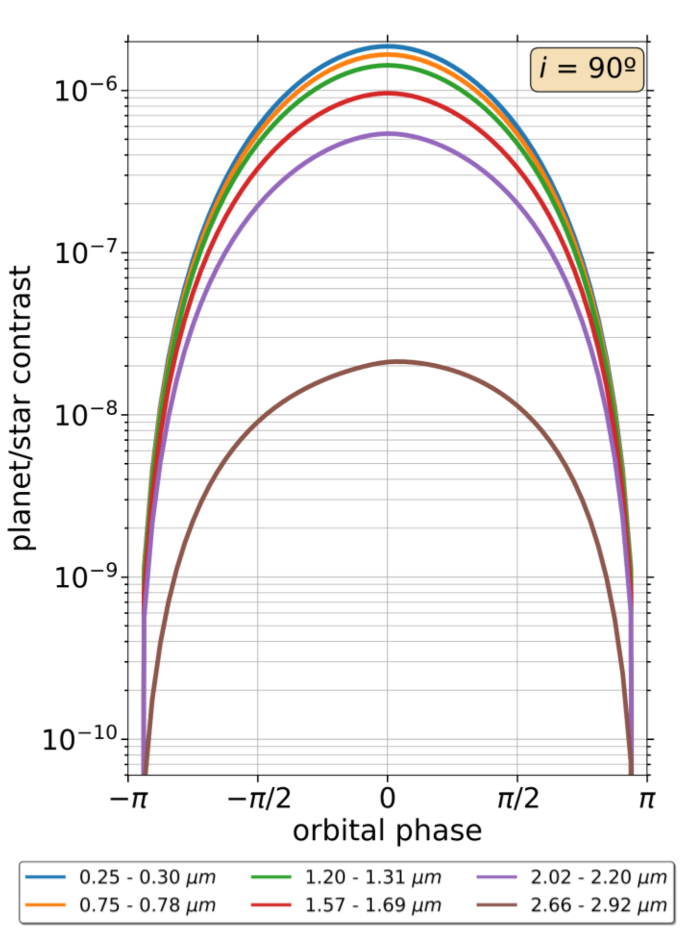
Planetary Parameter	**TRAPPIST-1 c**
Orbital Parameters	
Orbital Period, T $(Earth\ days)$	2.42
Semimajor axis, a (AU)	0.0158
Eccentricity, e	0
Obliquity (deg)	0
Installation$^{(1)}$, S $(W m^{-2})$	3015
Solid-body Parameters	
Radius, R $(10^6\ m)$	6.995
Surface gravity, g $(m\ s^{-2})$	10.65
Solid-body rotation period, P (s)	209 000
Solid-body rotation rate, Ω $(rad\ s^{-1})$	$3 \cdot 10^{-5}$

Notes: All planetary parameters were taken from Agol, et al., 2021.



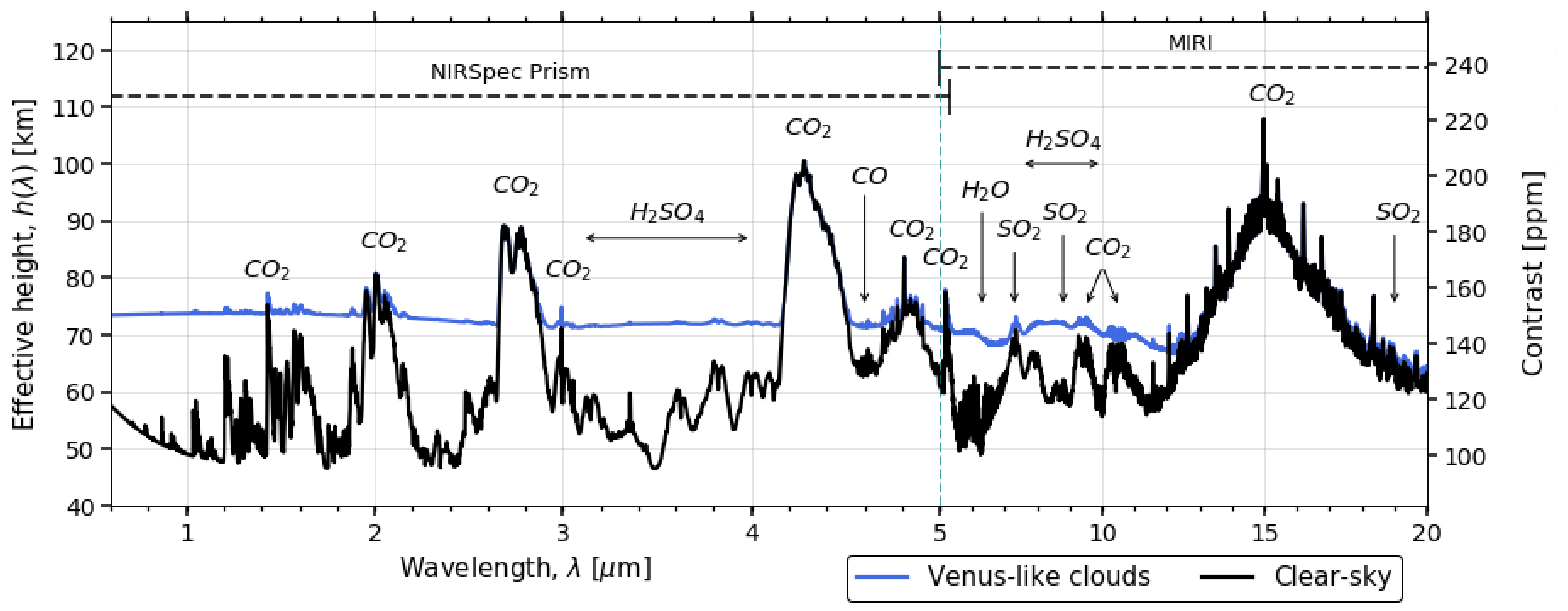
- Horizontal resolution: 64 x 48: 5.625º lon x 3.75º lat (TRAPPIST-1 c: 688 km x 458 km)
- Surface albedo: 0.2
- 18 soil layers with thermal inertia ground: 2000 J m^{-2} K^{-1} $s^{-1/2}$

Reflection phase curves



High albedo sulphuric acid aerosols lead to a contrast in the order of 10^{-6}

Transmission spectra



- Venus-like clouds in our model will screen most spectral features excepting the strongest CO_2
- 4.8 μm CO_2 feature might be detectable (**pressure broadening effect**) possibly suggesting a **high-pressure atmosphere**.

References used in this presentation

- Agol E, et al., 2021. Refining the Transit-timing and Photometric Analysis of TRAPPIST-1: Masses, Radii, Densities, Dynamics, and Ephemerides. The Planetary Science Journal. 2. 1. DOI: 10.3847/PSJ/abd022
- Haus R et al., 2013. Self-consistent retrieval of temperature profiles and cloud structure in the northern hemisphere of Venus using VIRTIS/VEX and PMV/VENERA-15 radiation measurements. Planetary and Space Science. 89: 77 – 101. DOI: 10.1016/j.pss.2013.09.020