Exo Venus atmospheres with the G-PCM

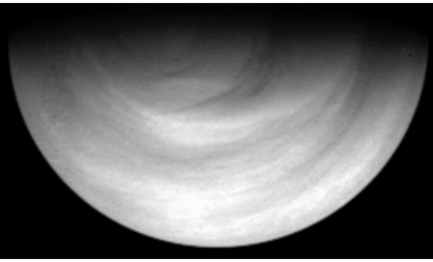
Gabriella Gilli[1,2]

D. Quirino[2], T. Navarro[3], M. Turbet[4], J. Leconte[7], S. Lebonnois[4], T. Fauchez[6], L. Kaltenegger[5], F. Selsis[7], E. Millour[4]

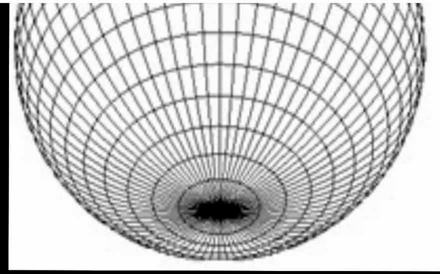
1. Instituto de Astrofísica de Andalucia (IAA), Granada, Spain 2. Instituto de Astrofísica e Ciências do Espaço (IA), Lisbon, Portugal 3. Trottier Space Institute, McGill Univ. Montreal, Canada 4. Laboratoire de Météorologie Dynamique (LMD), Paris, France, 5. Laboratoire d'Astrophysique de Bordeaux, Bordeaux, France, 6. NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA 7. Department of Astronomy, Carl Sagan Institute, Cornell University, Ithaca, USA

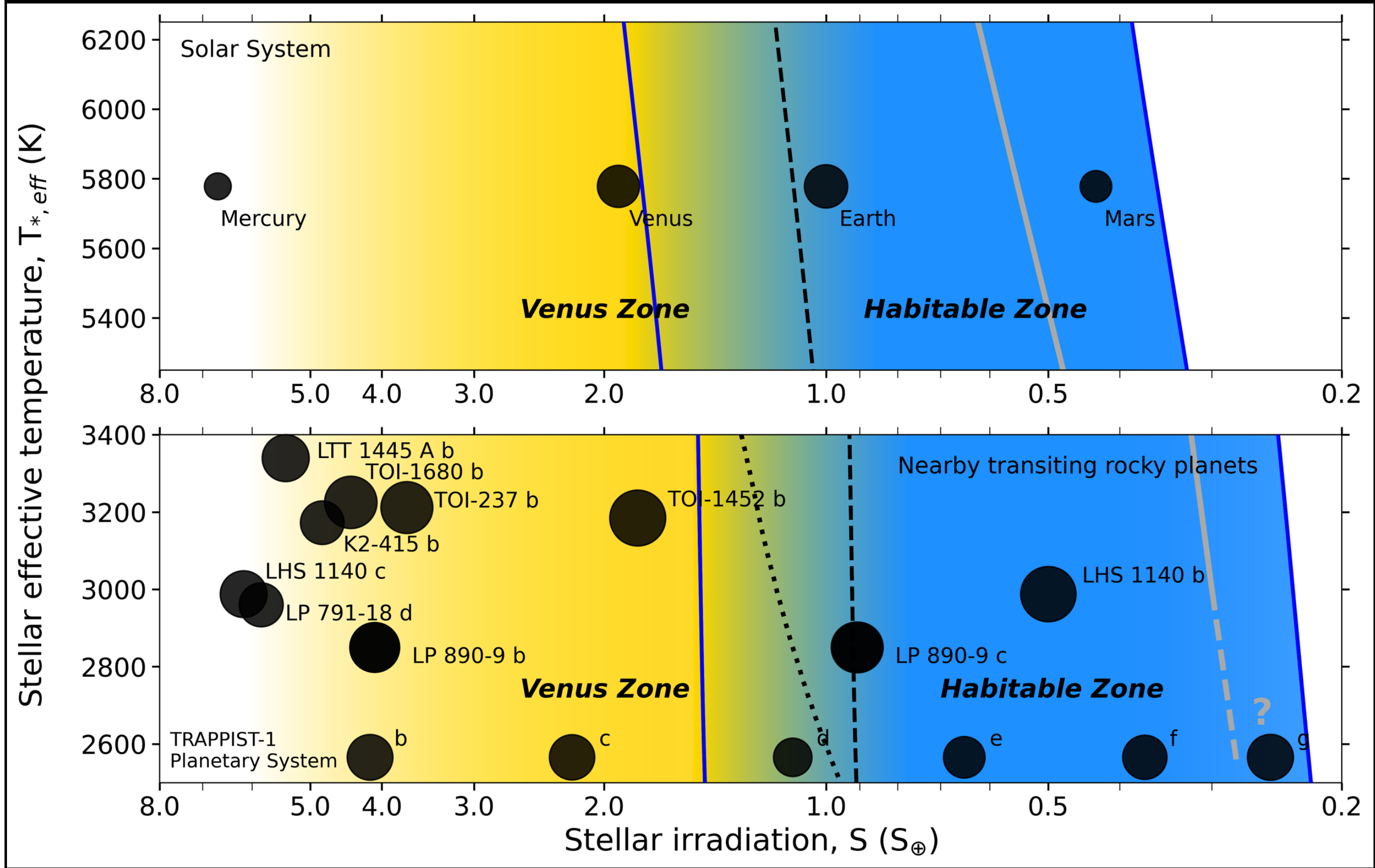
IAA Instituto de Astrofísica de Andalucía · Excelencia Severo Ochoa · CSIC · ia instituto de astrofísica e ciências do espaço · LMD

WORKSHOP Venus + Atmosphere, Japan, 03/2024



Venus as an exoplanet





Potential Venus-analogues

- LP 890-9 c (*Habitable zone*)
- Trappist-1c (*Venus zone*)

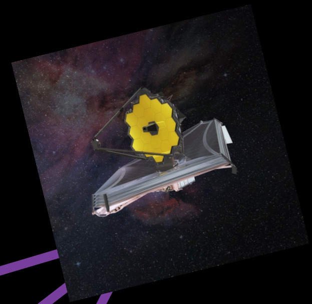
Adapted from Quirino, Gilli et al. 2023 MNRAS

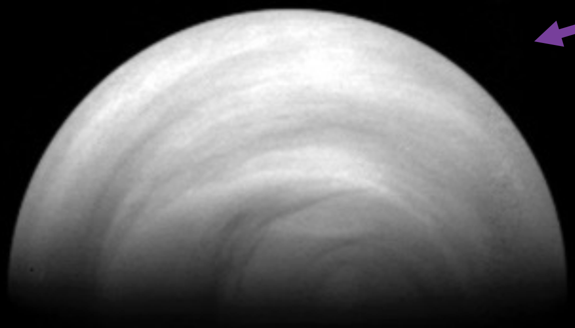
Building "virtual" planets using our Solar System planets as proxies

Generic-Planet Climate Model (G-PCM) for exoplanets and paleoclimate studies

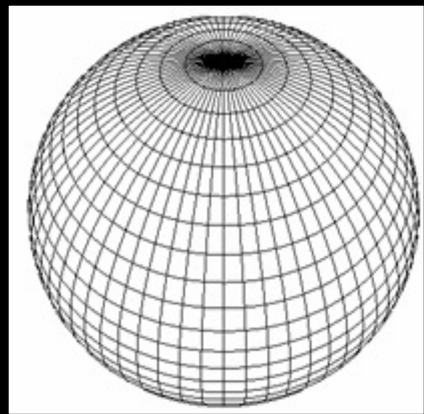
(Forget et al. 2014, Leconte et al 2013, Turbet et al. 2016,2021, Wordsworth et al. 2011, Fauchez et al. 2021, Quirino et al. 2023, Chaverot et al. 2022, 2023)

Observations





Reality

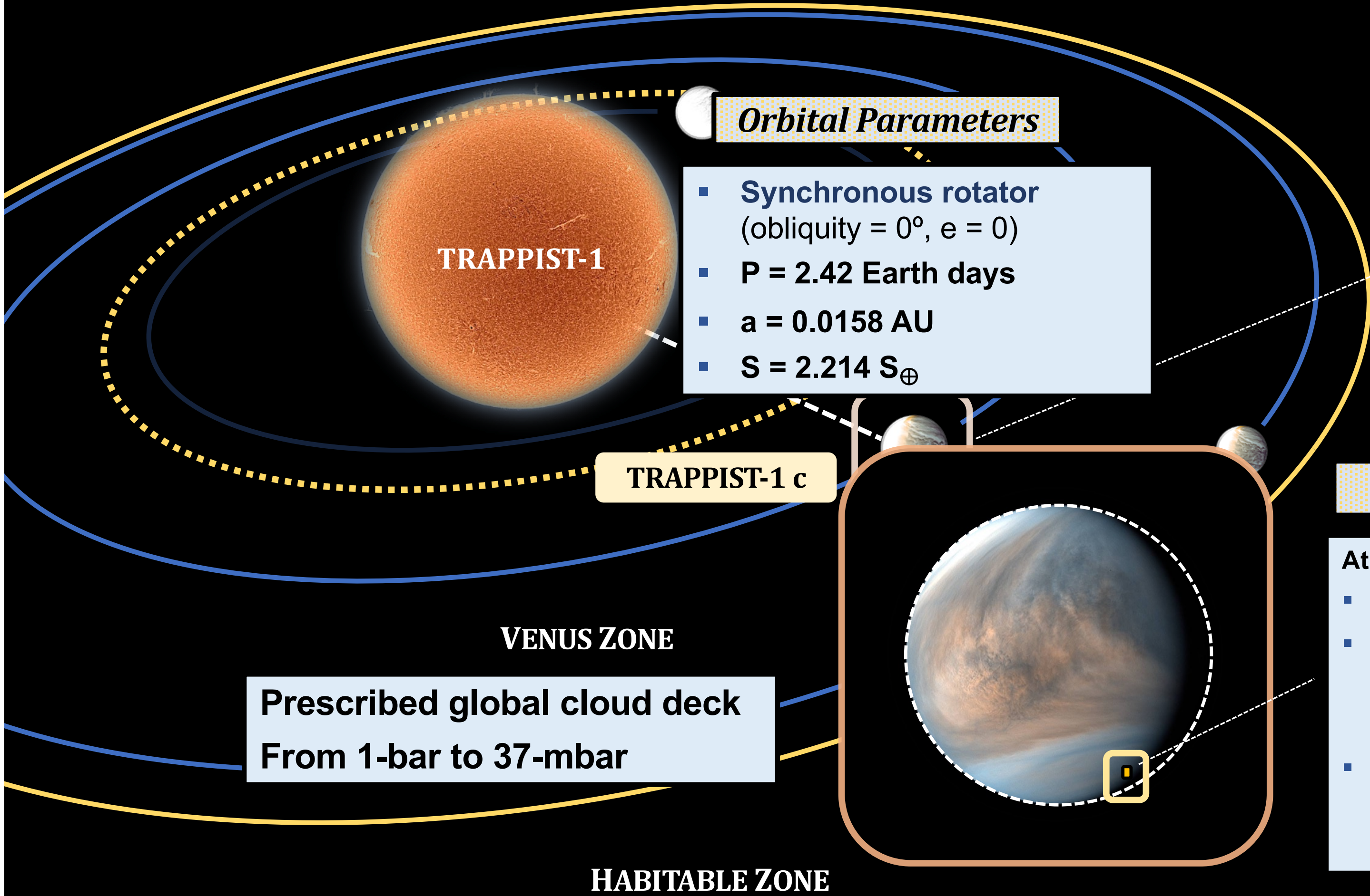


3D Model

- Model atmosphere of rocky exoplanets close to M-dwarf star
- Hypothesis:

Their atmosphere evolved into a modern-Venus

Venus-analogues with the Generic-PCM)



Orbital Parameters

- **Synchronous rotator** (obliquity = 0º, e = 0)
- **P = 2.42 Earth days**
- **a = 0.0158 AU**
- **S = 2.214 $S_\oplus$**

Solid-body Parameters

- **R = 6.995 $*$ 10^6 m** (1.097 $R_\oplus$)
- **g = 10.65 ms^{-2}** (1.086 $g_\oplus$)
- **Ω** = **3.0 $*$ 10^{-5} rad s^{-1}**
- **(M = 1.308 $M_\oplus$)**

Atmospheric Parameters

Atmosphere: Venus-like

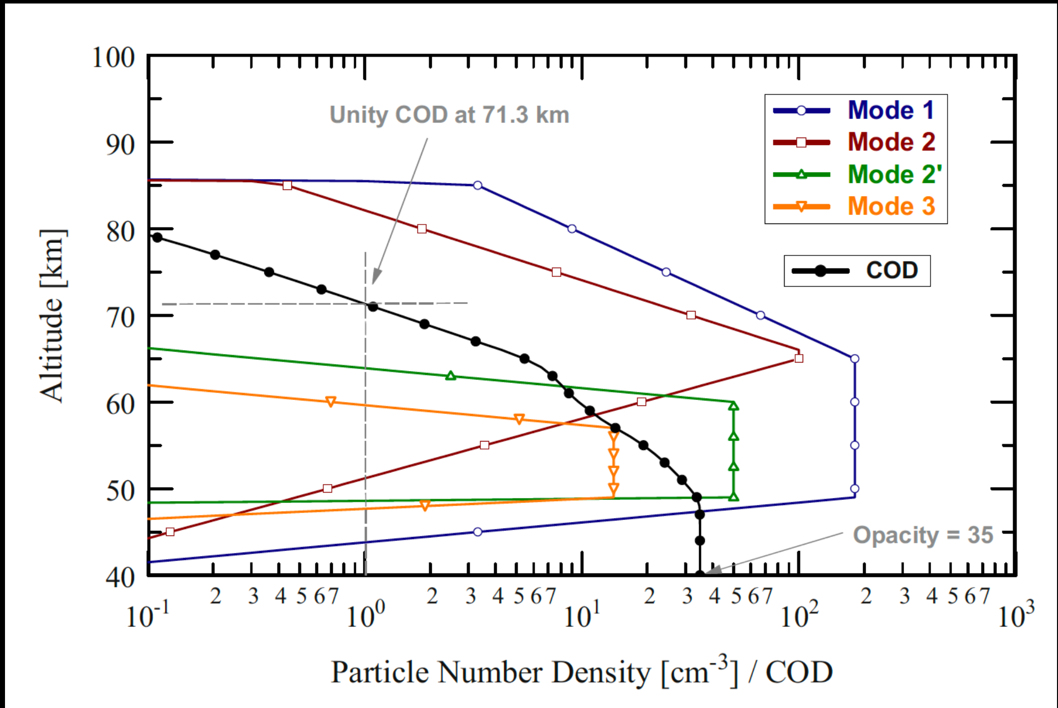
- **92-bar** surface atmospheric pressure;
- Similar chemical composition (**96.5% CO_2**; 180 ppm SO_2; 51.0 ppm OCS; 31.1 ppm H_2O; 12.0 ppm CO)
- Radiatively-active Venus-type clouds + UV absorber (following Garate-López & Lebonnois, 2018)

Prescribed global cloud deck
From 1-bar to 37-mbar

Courtesy of D.Quirino
This is a representative scheme. The star and planets, and the distances within are not to scale

Planetary data taken from: Agol et al., 2021

Aerosol distribution in the G-PCM for *Venus-analogues*



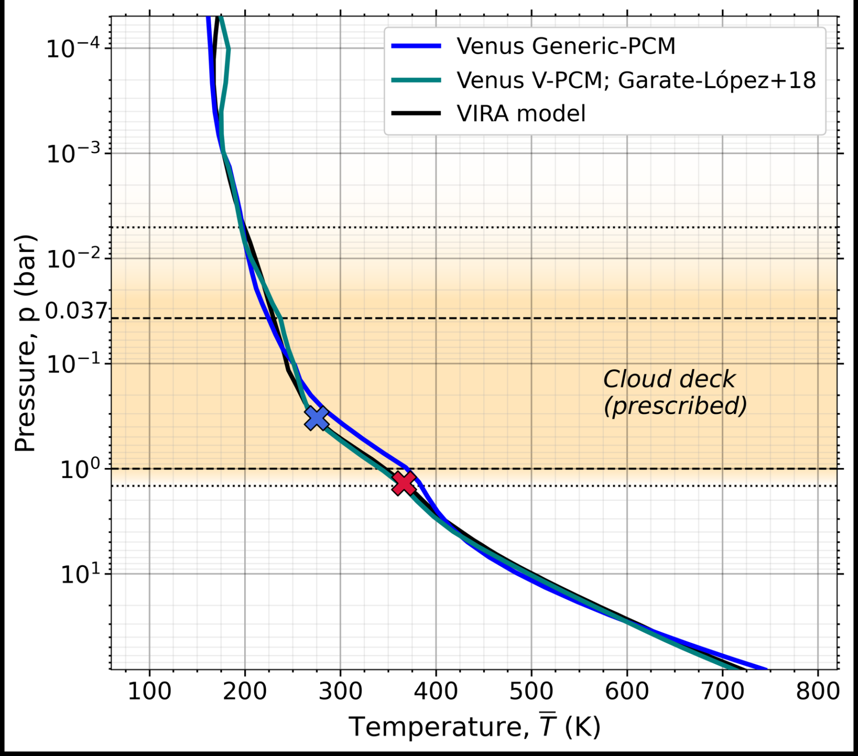
Aerosol	Mode 1	Mode 2	Mode 2p	Mode 3	"unknown" UV
Effective radius, R_{eff} (μm)	0.49	1.23	1.56	4.25	0.5
Effective variance, ν_{eff} (μm^2)	0.21	0.067	0.044	0.062	0.1
Top pressure, p_t (bar)	0.1	0.1	0.23	0.4	0.037
Base pressure, p_b (bar)	1	0.11	1	1	0.33

Aerosols as function of their size following Venus Express observations

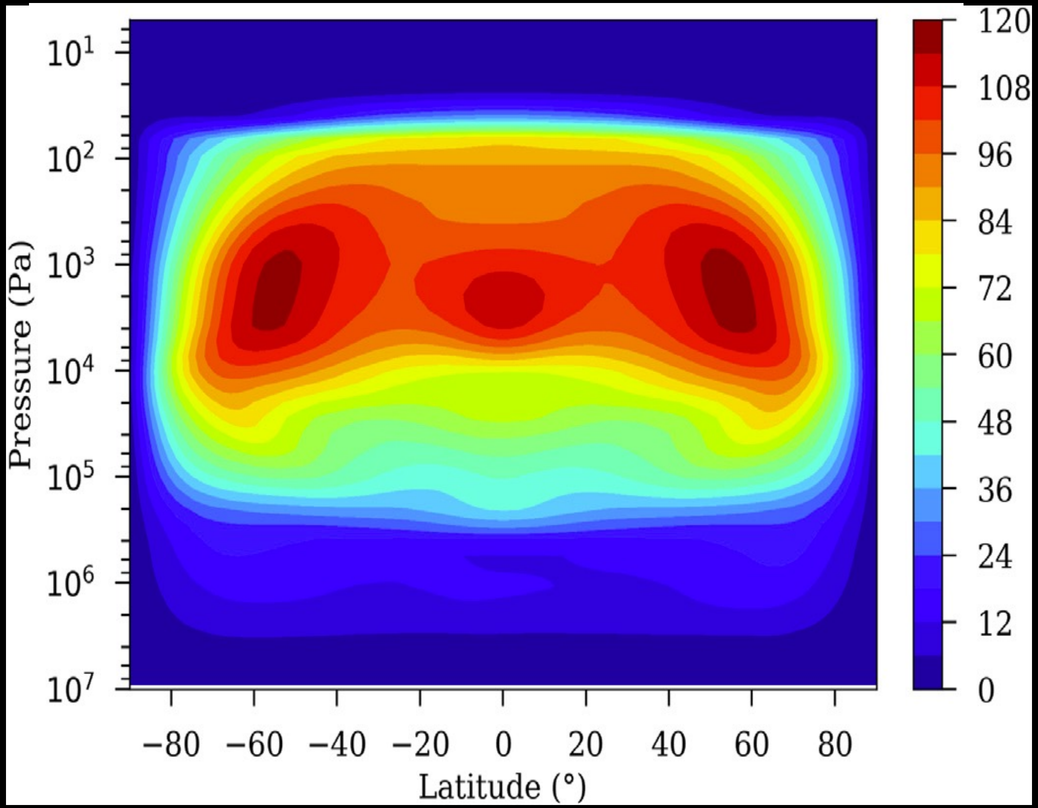
From Haus et al. 2014, 2015 model

Presence of cloud essential to maintain the superrotation

Validation test: Venus simulated with the G-PCM



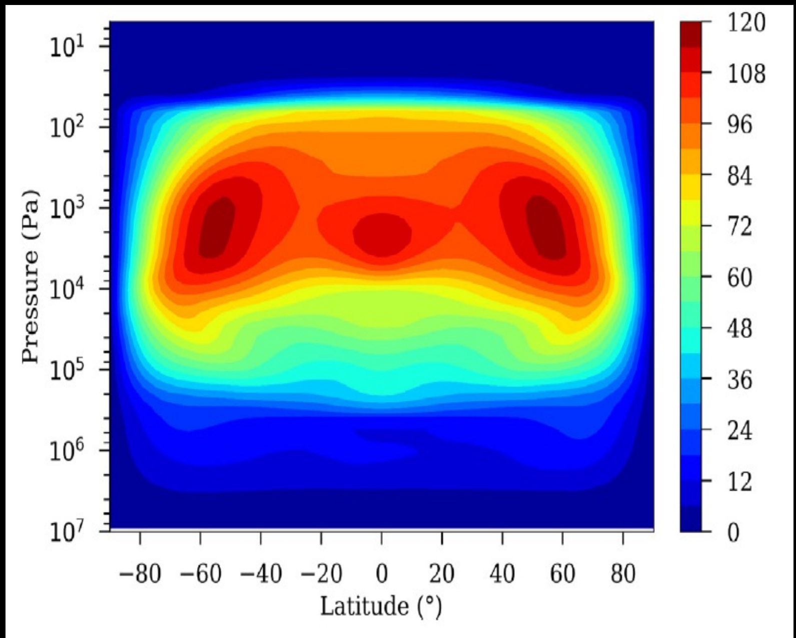
Courtesy of D.Quirino



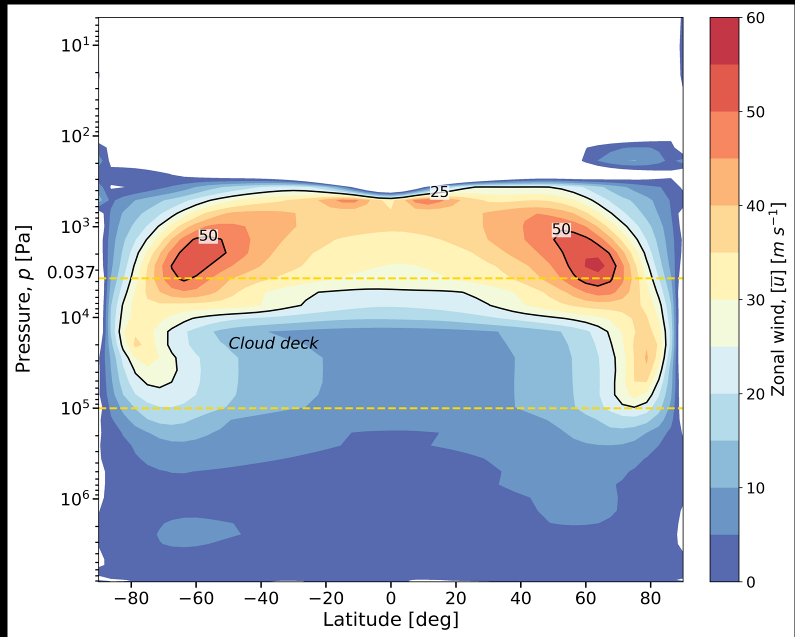
Garate-Lopez & Lebonois 2018

“VALIDATION” of Venus-like G-PCM simulations

ZONA WINDS: SUPERROTATION



V-PCM: *Garate-Lopez & Lebonnois 2018*

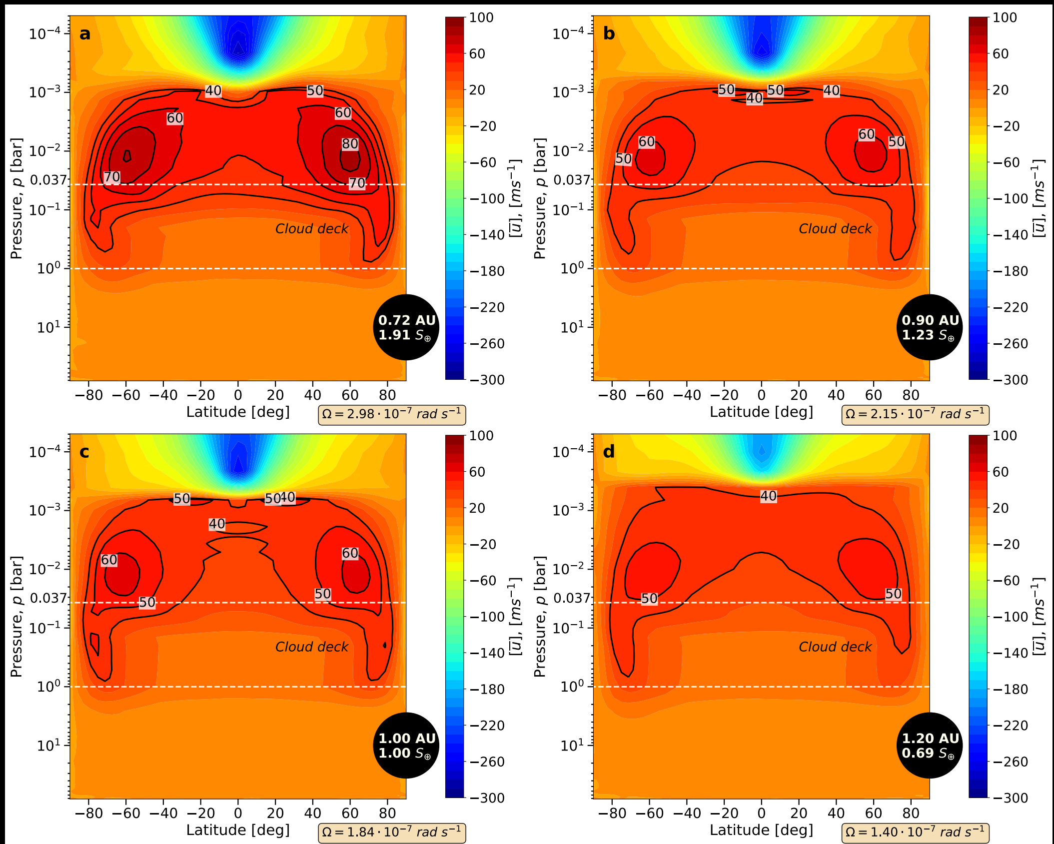


G-PCM: *Forget et al. In preparation*

- Generic-GCM reproduces the superrotation regime: pressure range, wind speed, high-latitudes jets;
- Reasonable agreement between the two models except for the equatorial jet and the amplitude of the maximum

“VALIDATION” of Venus-like G-PCM simulations

ZONA WINDS: variation with Insolation/orbital distance



Orbital distance r, $[AU]$	Rotation rate Ω, $[rad\,s^{-1}]$	Tangential velocity (1) v_t , $[m\,s^{-1}]$	Maximum zonal wind speed (2) $[\overline{u}]$, $[m\,s^{-1}]$	Ratio $[\overline{u}] : v_t$
0.72	$2.98 \cdot 10^{-7}$	1.80	83.8	46.6
0.90	$2.15 \cdot 10^{-7}$	1.30	63.9	49.2
1.00	$1.84 \cdot 10^{-7}$	1.11	65.8	59.3
1.20	$1.40 \cdot 10^{-7}$	0.85	57.5	67.6

- Overall *decrease* in zonal wind speed with *decreasing* insolation (weaker day-to-night energy redistribution)
- Zonal wind structure remains present in all 4 orbital distances:

Superrotation is a robust dynamical feature in this insolation range.

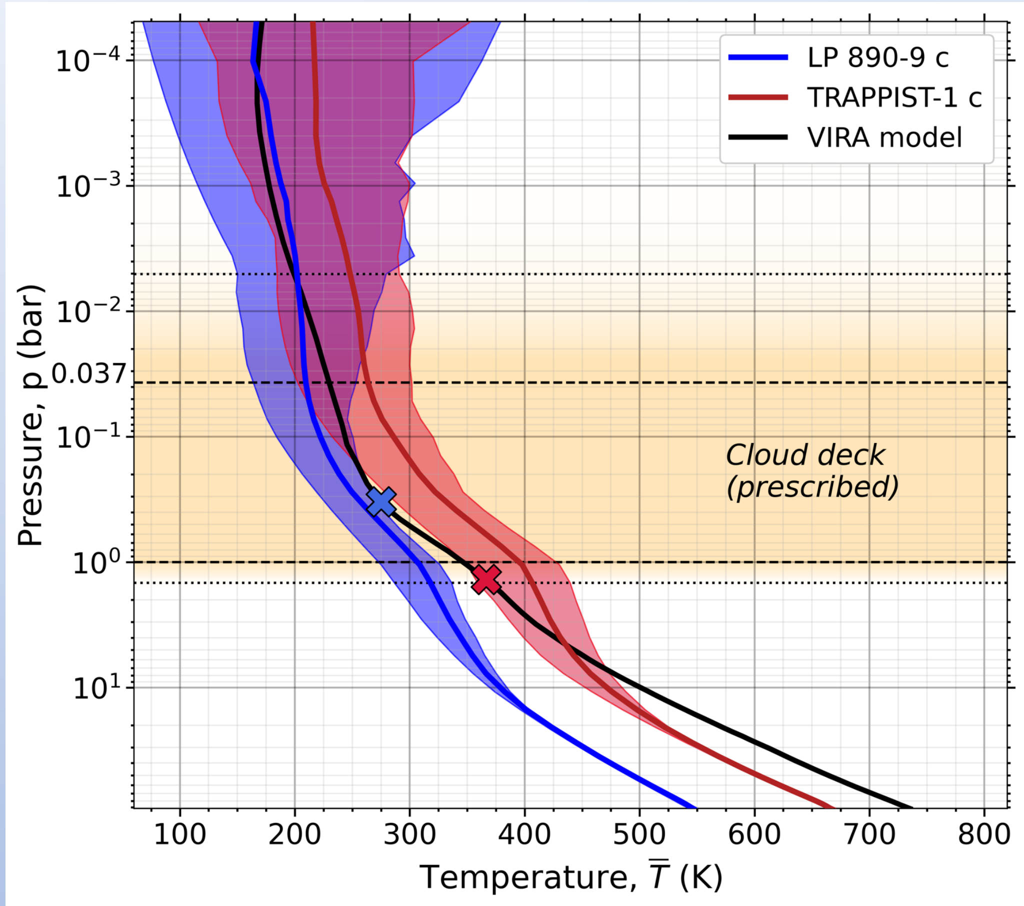
Planetary parameters of potential Venus-analogues

Table 1. Planetary parameters used in the Generic-PCM for the simulations of a modern Venus-like atmosphere

Parameter / Planet	LP 890-9 b	LP 890-9 c	TRAPPIST-1 c	TRAPPIST-1 d
Host star spectral type	M6V	M6V	M8V	M8V
Distance, d (pc)	32.4	32.4	12.4	12.4
Orbital Period, T (days)	2.73	8.46	2.42	4.05
Semimajor axis, a (AU)	0.01875	0.03984	0.01580	0.02227
Stellar irradiation, S ($W\ m^{-2}$)	5569	1234	3015	1518
Stellar irradiation, S ($S_\oplus$)	4.09	0.91	2.21	1.12
Radius, R (km)	8410	8709	6995	5026
Radius, R ($R_\oplus$)	1.32	1.37	1.10	0.788
Gravitational acceleration, g ($m\ s^{-2}$)	13.19	13.35	10.65	6.11
Solid-body rotation period, P (s)	236 000	730 700	209 000	350 000
Solid-body rotation rate, Ω ($rad\ s^{-1}$)	2.66×10^{-5}	8.60×10^{-6}	3.00×10^{-5}	1.80×10^{-5}
Radiative imbalance at TOA ($W\ m^{-2}$)	1.5 – 2	< 1	< 1	< 1
Number of orbits of the simulation	40k	12k	25k	40k
References	Delrez+2022	Delrez+2022	Agol+2021	Agol+2021

Eccentricity and Obliquity are set to 0.

Temperature profiles: LP 890-9 c and TRAPPIST-1 c

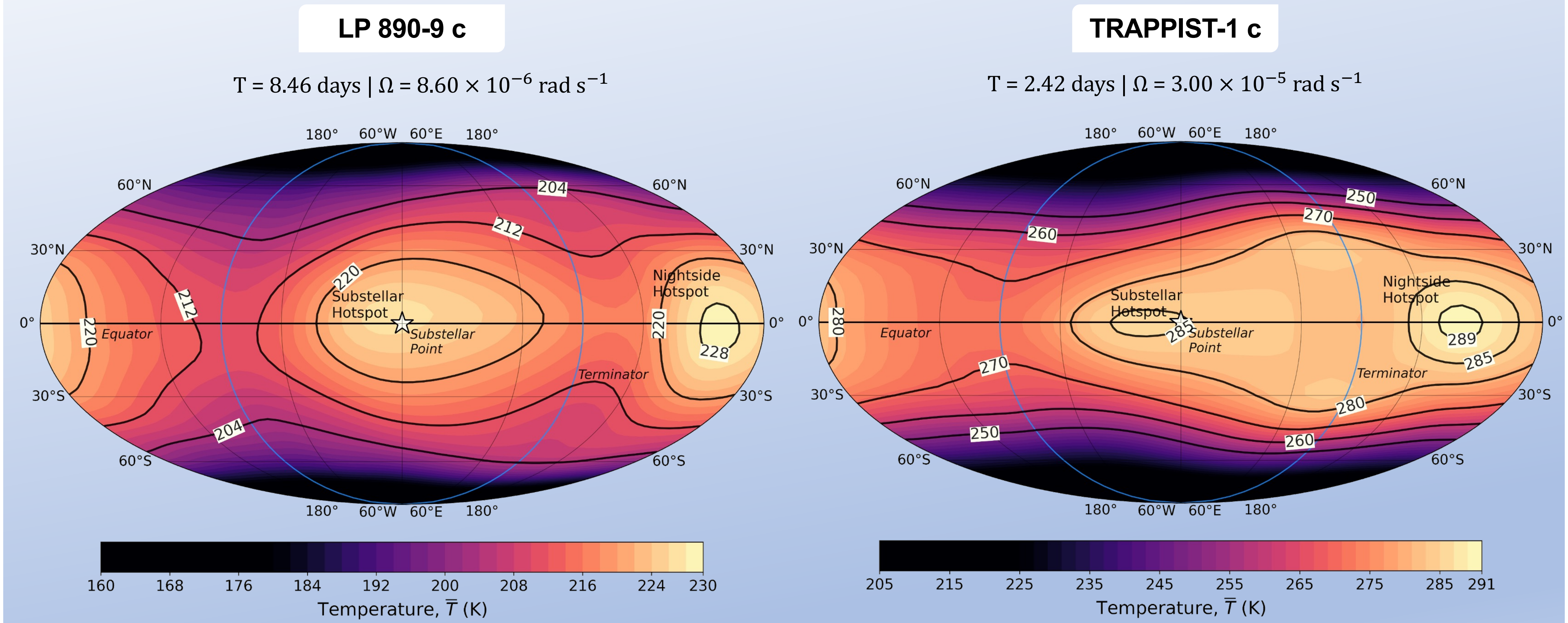


H_2SO_4 condensation point: p ~ 1.38-bar; T ~ 366 K

H_2SO_4 freezing point: p ~ 0.33-bar; T ~ 275 K

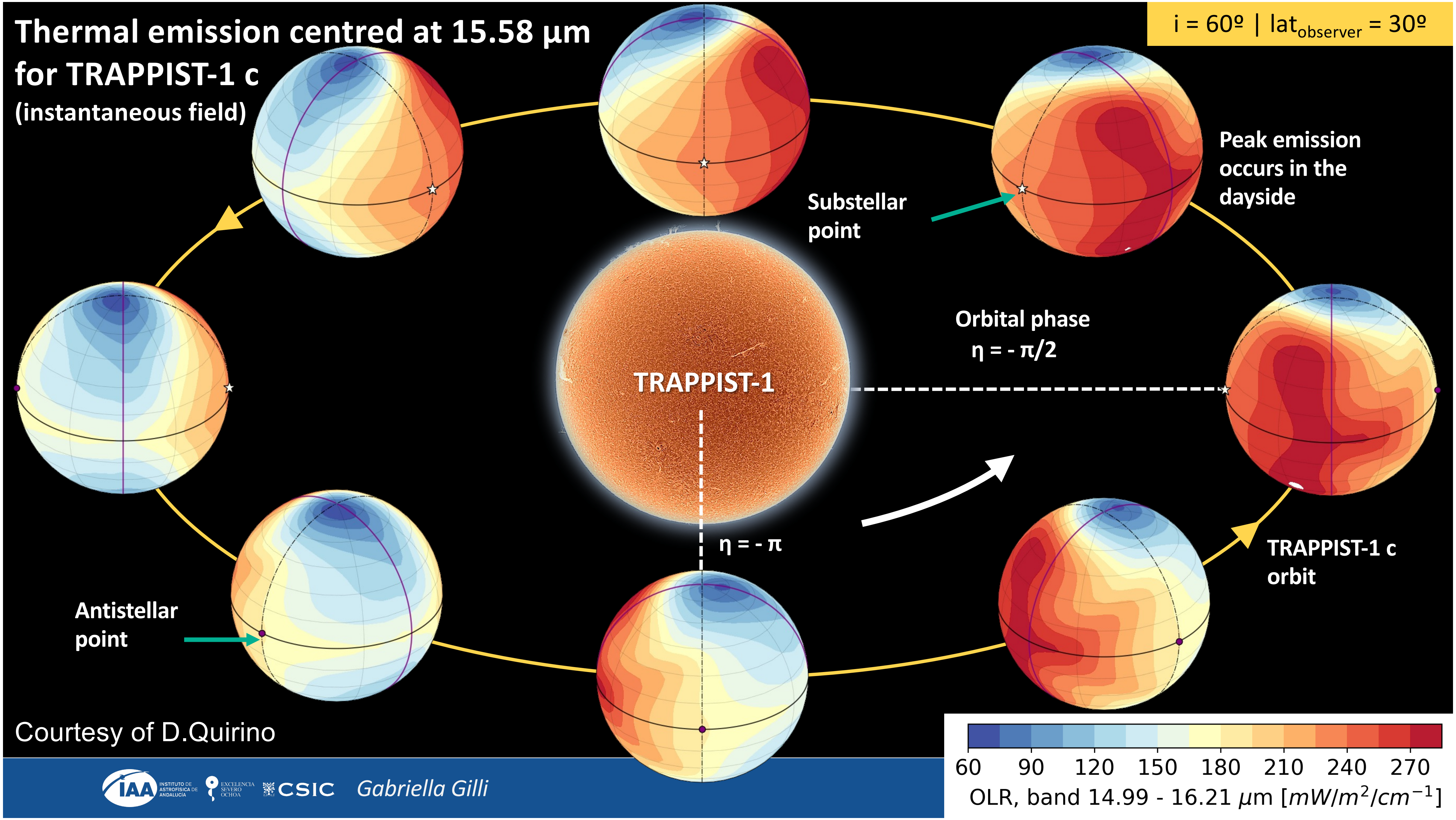
Temperature at the cloud top (p ~ 37-mbar)

Time-mean: 10 orbits average

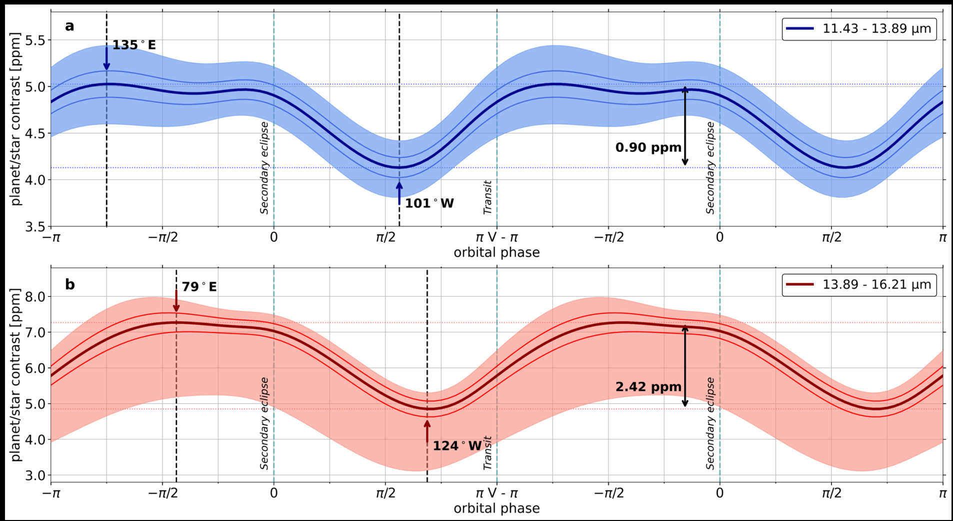


Adapted from Quirino et al. (2023) and Quirino et al. (in prep.)

Hot-spot eastward the substellar point → strong equatorial jet



Thermal emission centred at 15.58 µm for TRAPPIST-1 c
(instantaneous field)
i = 60º | lat$_{observer}$ = 30º
Peak emission occurs in the dayside
Substellar point
Orbital phase η = - π/2
TRAPPIST-1
η = - π
TRAPPIST-1 c orbit
Antistellar point
Courtesy of D.Quirino
60 90 120 150 180 210 240 270
OLR, band 14.99 - 16.21 µm [mW/m^2/cm^{-1}]
Gabriella Gilli

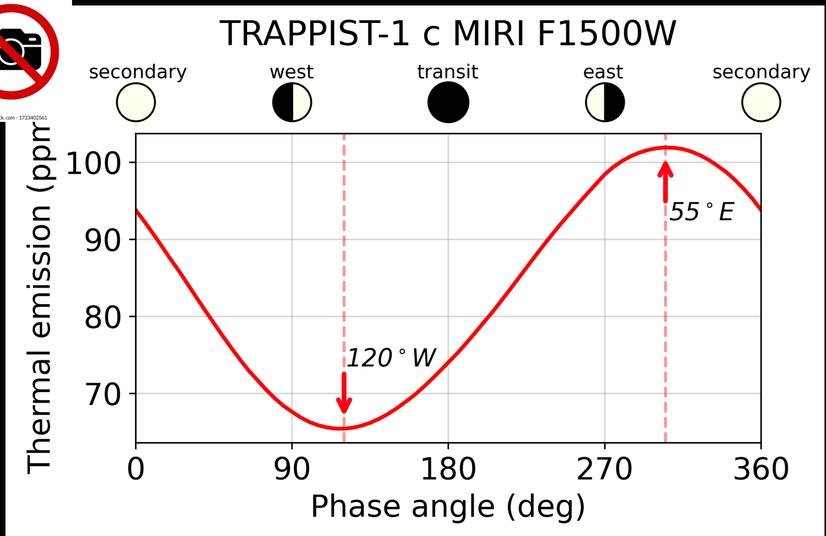


Predicted emission phase curve of *LP 890-9c*

(time-averaged over 10 orbits)

- Largest contrast are between 5 and 7 ppm for continuum and 15-μm CO_2 bands, respectively
- Largest amplitude modulation is 2.4 ppm, not detectable with current instruments

Quirino, Gilli et al. 2023 MNRAS letter

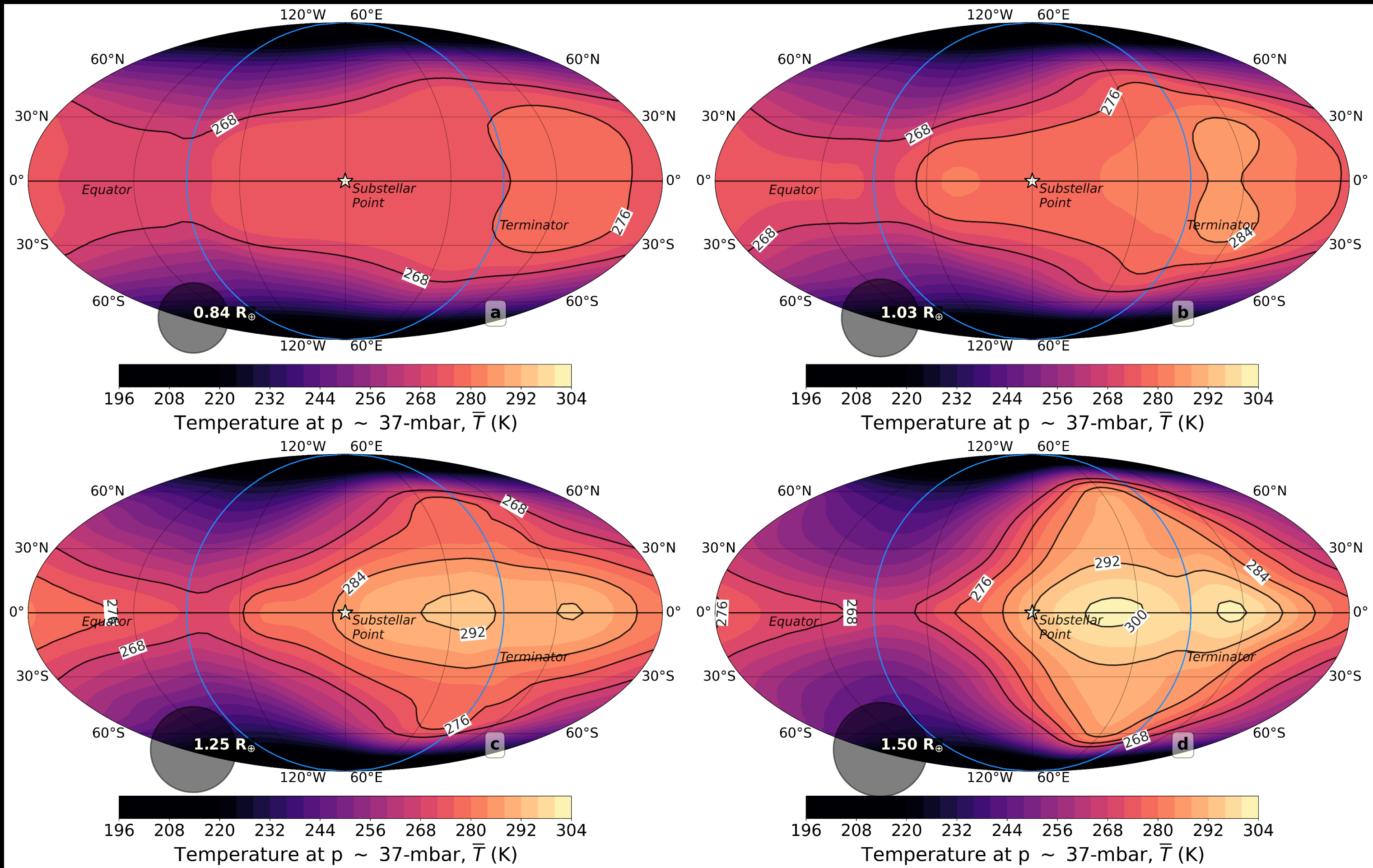


Predicted emission phase curve of *Trappist 1c*

- Largest contrast are between 215 and 100 ppm for continuum (~18-μm) and 15-μm CO_2 bands, respectively.
- 3D model confirmation of no thick Venus atmosphere (*contrast below* JWST obs at 15um ~400 ppm)
- Largest amplitude modulation is ~45 ppm at 15 μm

Quirino, Gilli et al., in preparation

Mass-radius relationships: temperature at the cloud top (p ~ 37-mbar)



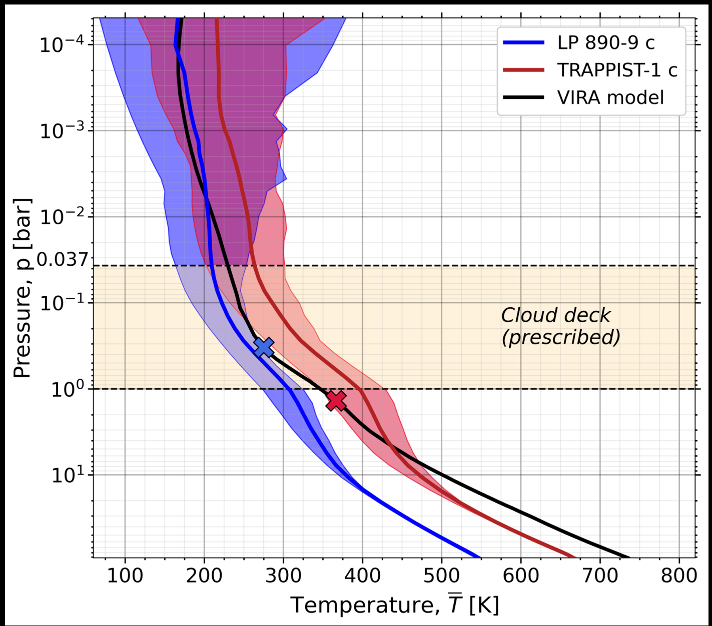
LARGER RADII LEAD TO:

- Warmer cloud top temperature field;
- Smaller eastward shift of the temperature maximum;
- Two high-latitudes (~60º N/S) temperature maxima in the largest two radii

Quirino et al. in preparation

FUTURE WORK / LINES OF IMPROVEMENTS

1. change the altitude range of the prescribed clouds to evaluate the impact on the radiative budget and on the synthetic observable



Master student at IAA Working on that right now!

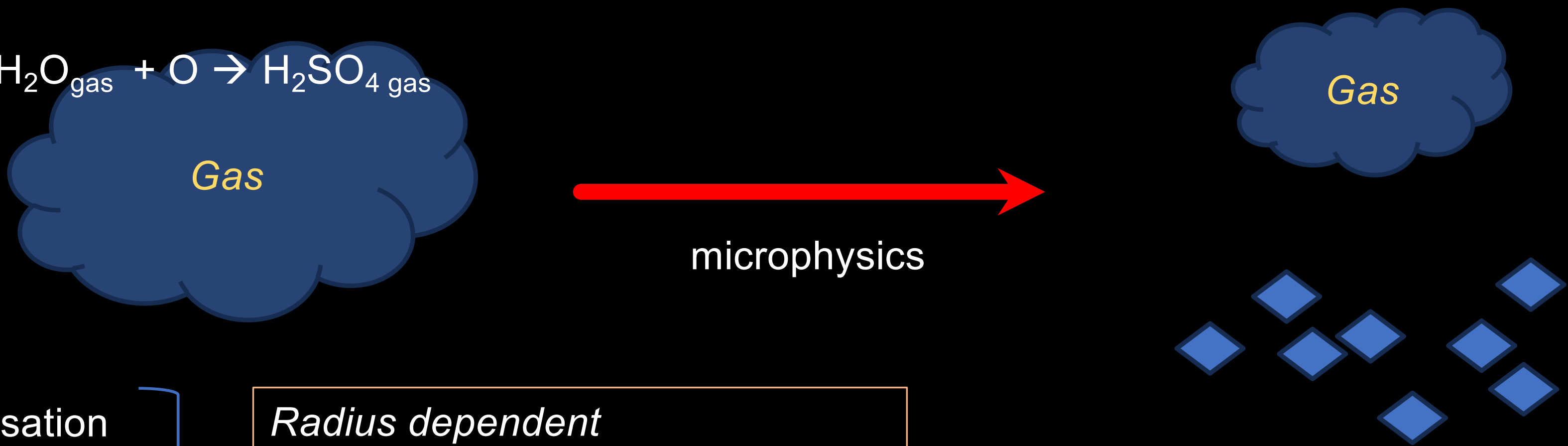
X H_2SO_4 condensation point: p ~ 1.38-bar; T ~ 366 K

X H_2SO_4 freezing point: p ~ 0.33-bar; T ~ 275 K

FUTURE WORK

2. Implement a *simplified microphysical Venus-like cloud model* into the GCM (following Stolzenbach et al. 2023) to form H_2SO_4-H_2O droplets in the atmosphere of the exoplanets “interactively”

$SO_2 + H_2O_{gas} + O \rightarrow H_2SO_{4\ gas}$



$H_2SO_{4\ gas} + H_2O_{gas} \rightarrow (H_2SO_4 + H_2O)_{liq}$

Condensation
Evaporation
Coagulation

Radius dependent

- fix radius and σ_g
- calculate H_2SO_4 weight fraction as function of water T-p profiles