

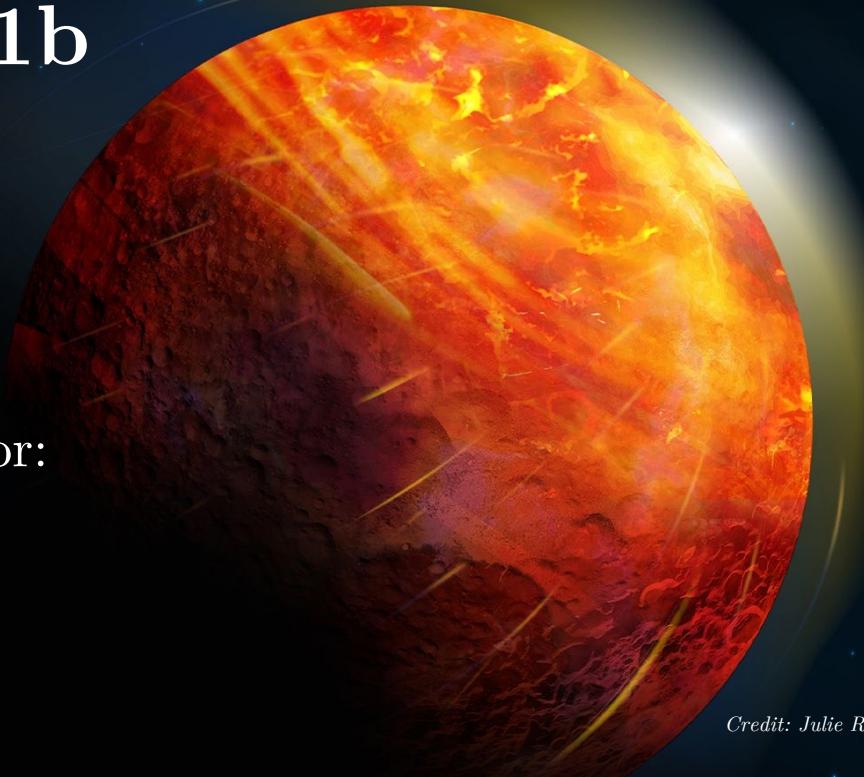
# Studying radiative transfer in the evolving atmosphere of lava planet K2-141b

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July 2025



*Credit: Julie Roussy, McGill Graphic Design*

# What is a lava planet?

- Exoplanet
- Rocky composition
- Surface temperatures high enough to melt rock



*Credit: Geoffrey Marchal*

- Permanent dayside and nightside
- Magma oceans
- Vaporized rock atmosphere on dayside
- Atmosphere collapses through rock rain before nightside



*Artistic rendering (AI generated)*

# Index

I. Motivation

II. Objectives & Hypothesis

III. Theoretical background

IV. Methodology

V. Results

VI. Conclusions



*Credit: Geoffrey Marchal*

# I. MOTIVATION



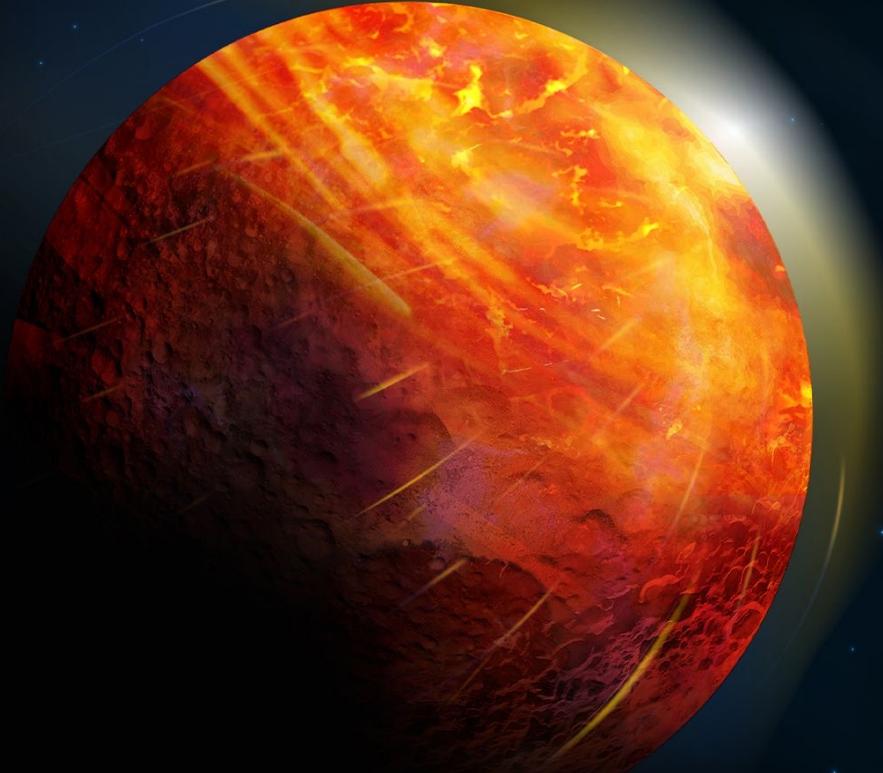
# I. MOTIVATION

- Atmosphere coupled to interior
- Unique geological processes and extreme climates
- Early stages of planetary formation of rocky planets



*Artistic rendering (AI generated)*

# II. OBJECTIVES & HYPOTHESIS



# II.I Objectives



- Calculate atmospheric opacity (Code 1)
- Calculate stellar and surface radiation absorbed by the atmosphere (Code 2)
- Analyze K2-141b's atmosphere in early stages and late stages

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## II.II Hypothesis



### EARLY STAGE /STAGE 1

- Optically thicker
- Higher absorbed flux



### LATE STAGE /STAGE 4

- Lower opacity
- Lower absorbed flux



*Evolution of K2-141b*



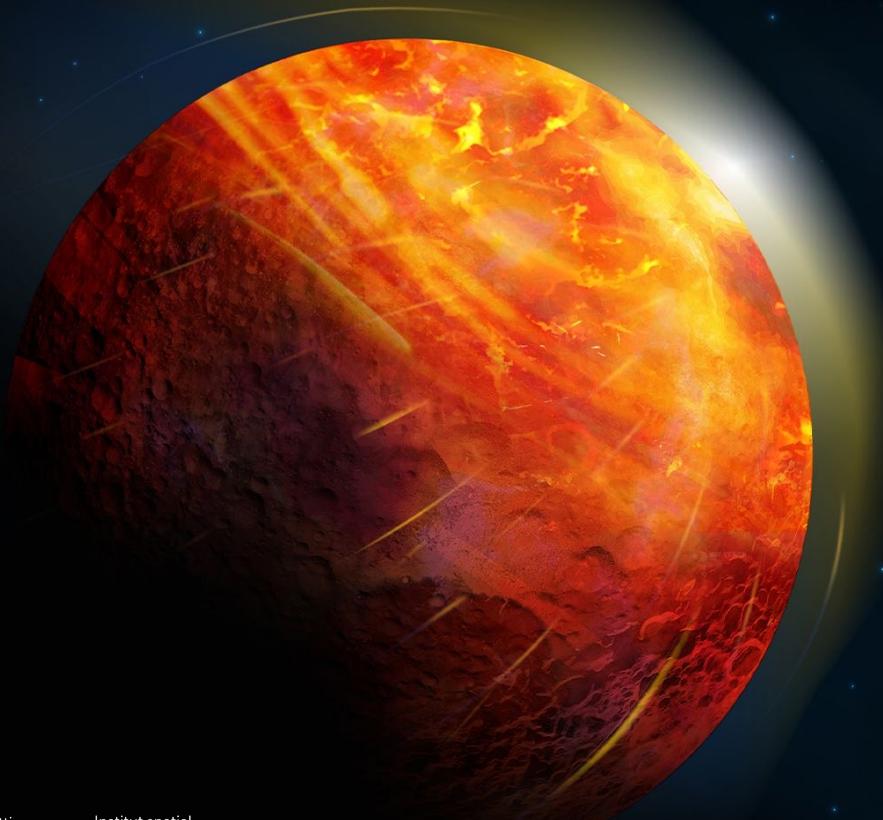
Changes in:

- (i) Magma ocean composition
- (ii) Surface temperature

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# III.

## THEORETICAL BACKGROUND

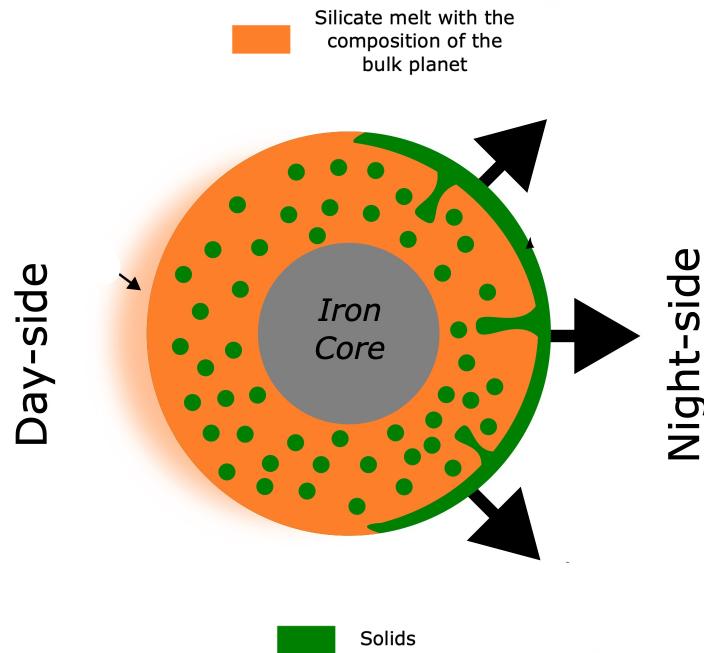


# III.I Evolutionary stages of a lava planet



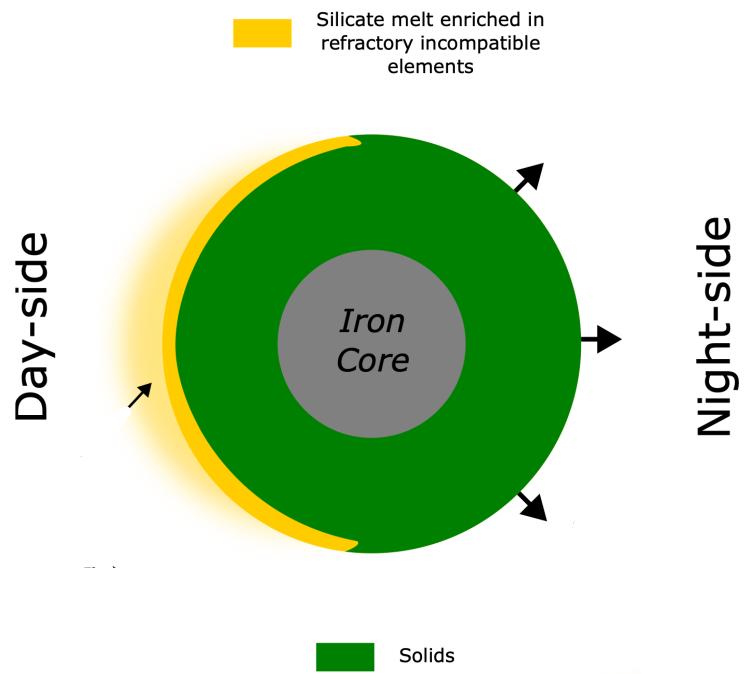
## STAGE 1/GMO

- Deep magma ocean on both sides
- Horizontal and vertical convection
- Geothermal flux:  $10^5 \text{ W/m}^2$
- Homogenized rocky composition



Credit: Dr. Boukare

# III.I Evolutionary stages of a lava planet



## STAGE 4/SMO

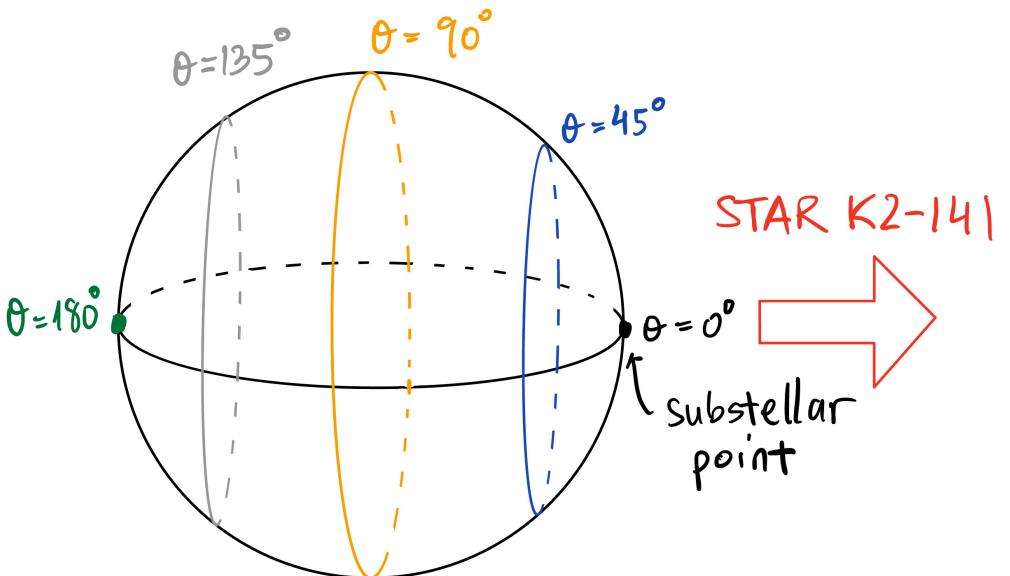
- Shallow magma ocean on dayside
- Maintained through stellar radiation
- Dynamically inactive
- **Composition:** FeO, SiO, SiO<sub>2</sub>

Credit: Dr. Boukaré

## III.II Co-latitude



- Co-latitude / angular distance from substellar point  $\theta$



$$\theta(\lambda_l, \phi_l) = \cos^{-1}(\cos \phi_l \cos \lambda_l)$$

K2-141b

Artistic rendering (AI generated)



# III.III Different regions in K2-141b



Fully illuminated

$$\theta \in (0^\circ, \theta_f)$$



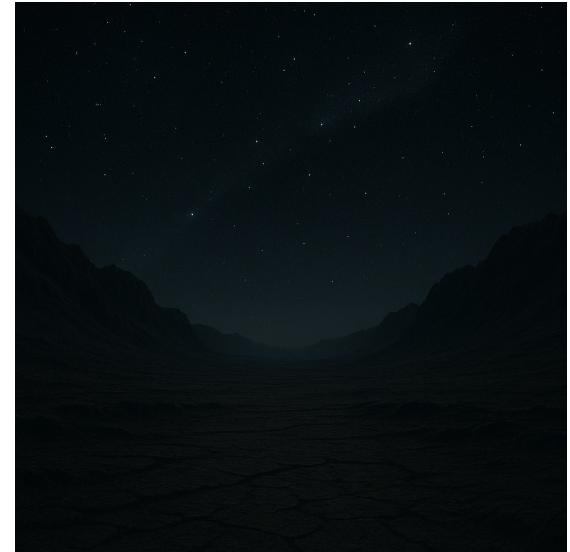
Penumbra

$$\theta \in (\theta_f, \theta_d)$$



Nightside

$$\theta \in (\theta_d, 180^\circ)$$



$$\theta_f = (64, 37 \pm 0, 81)^\circ$$

$$\theta_d = (114, 54 \pm 0, 79)^\circ$$

*Artistic rendering (AI generated)*



## III.IV Incident stellar flux

$$F_*(\lambda, \theta) = \begin{cases} F_{\text{stel},f}(\theta) = \pi \int_0^{\infty} J_f(\theta) B(\lambda, T_*) d\lambda, & \theta \in (0^\circ, \theta_f) \\ F_{\text{stel},p}(\theta) = \pi \int_0^{\infty} J_p(\theta) B(\lambda, T_*) d\lambda, & \theta \in (\theta_f, \theta_d) \\ 0, & \theta \in (\theta_d, 180^\circ) \end{cases}$$

$$T_* = (4,57 \pm 0,10) \times 10^3 \text{ K}$$

# III.V Surface temperature



Fully illuminated

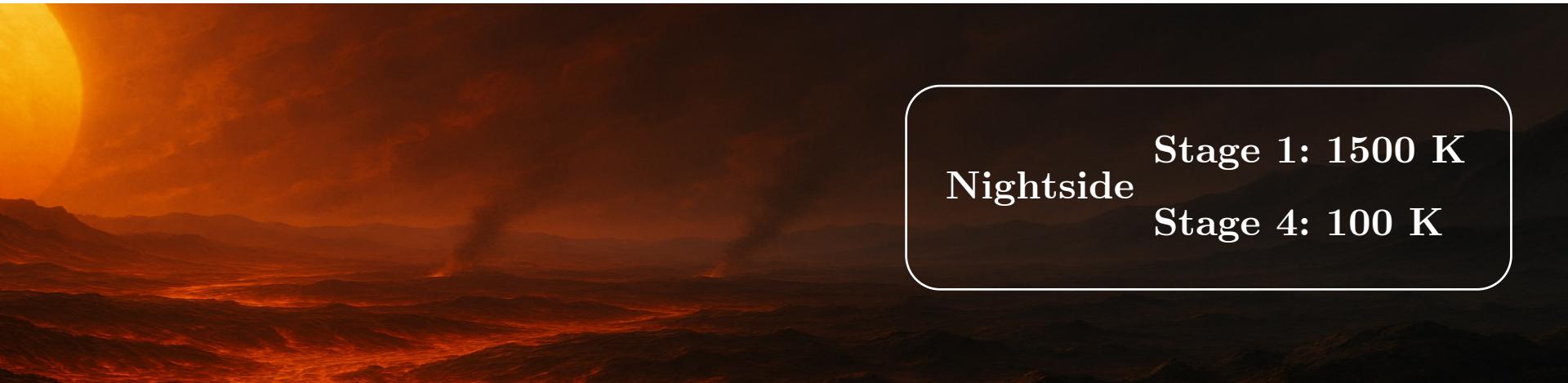
$$T_{\text{surf}}(\theta) = \left( \frac{F_{\text{stel},f}(\theta) + F_{\text{geo}}(\text{Stage})}{\sigma} \right)^{1/4}.$$

Penumbra

$$T_{\text{surf}}(\theta) = \left( \frac{F_{\text{stel},p}(\theta) + F_{\text{geo}}(\text{Stage})}{\sigma} \right)^{1/4}.$$

Radiative  
equilibrium!

Nightside      Stage 1: 1500 K  
                    Stage 4: 100 K



Artistic rendering (AI generated)

# III.VI Optical properties of the atmosphere



- Optical depth of  $i\epsilon\mathcal{A}$ :

$$\tau_i(\lambda, P_i, P_{\text{atm}}, T_{\text{atm}}) = \frac{x_i(\lambda, P_{\text{atm}}, T_{\text{atm}})P_i}{m_i g_p}.$$

- Total opacity at co-latitude  $\theta$ :

$$\epsilon_{\text{total}}(\lambda, \theta) = 1 - e^{-\sum_{i \in \mathcal{A}} \tau_i(\lambda, \theta)} \in [0, 1].$$

$$\mathcal{A} = \{\text{SiO}, \text{SiO}_2, \text{Na}, \text{O}_2, \text{AlO}, \text{TiO}, \text{MgO}, \text{CaO}, \text{K}\}$$

# III.VII Radiative transfer formulation



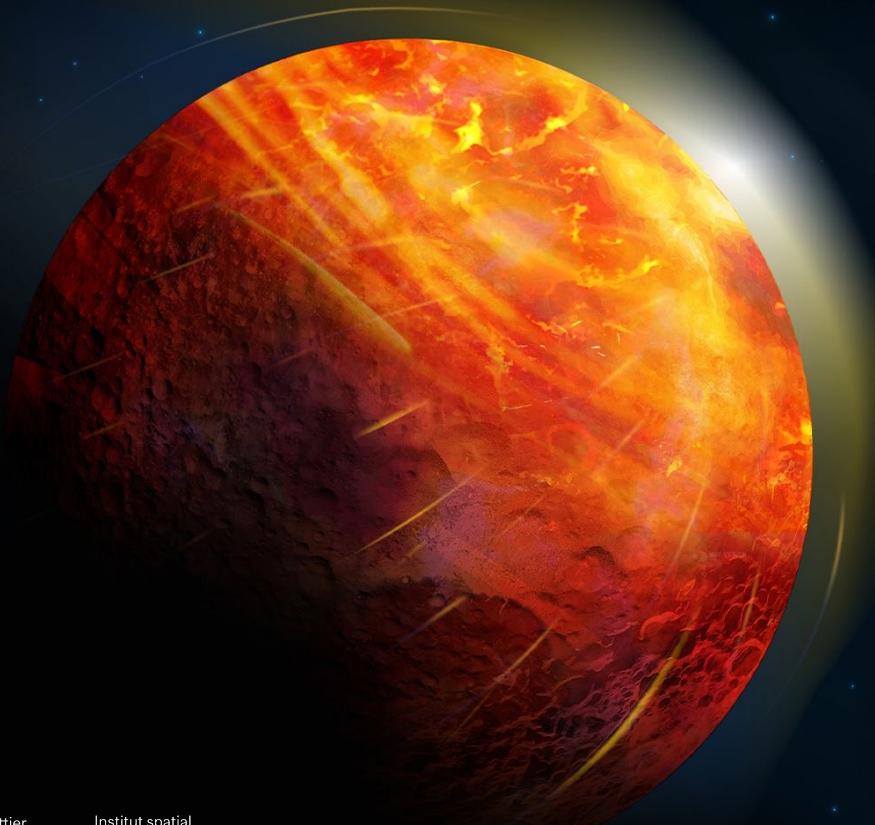
- Stellar flux absorbed by the atmosphere at co-latitude  $\theta$ :

$$F_{\text{stel}}(\theta) = \int_0^{\infty} \epsilon_{\text{total}}(\lambda, \theta) F_*(\lambda, \theta) d\lambda.$$

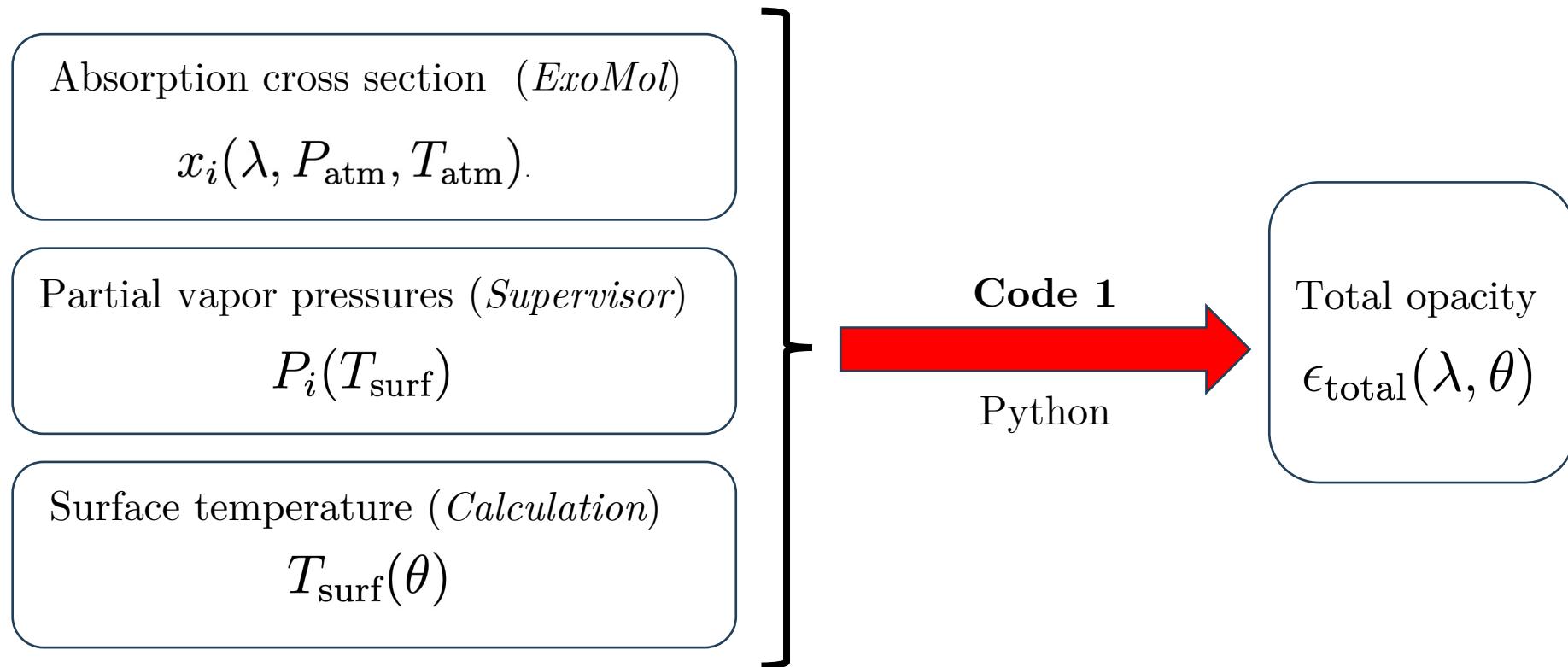
- Surface flux absorbed by the atmosphere at co-latitude  $\theta$ :

$$F_{\text{surf}}(\theta) = \pi \int_0^{\infty} \epsilon_{\text{total}}(\lambda, \theta) B(\lambda, T_{\text{surf}}(\theta)) d\lambda.$$

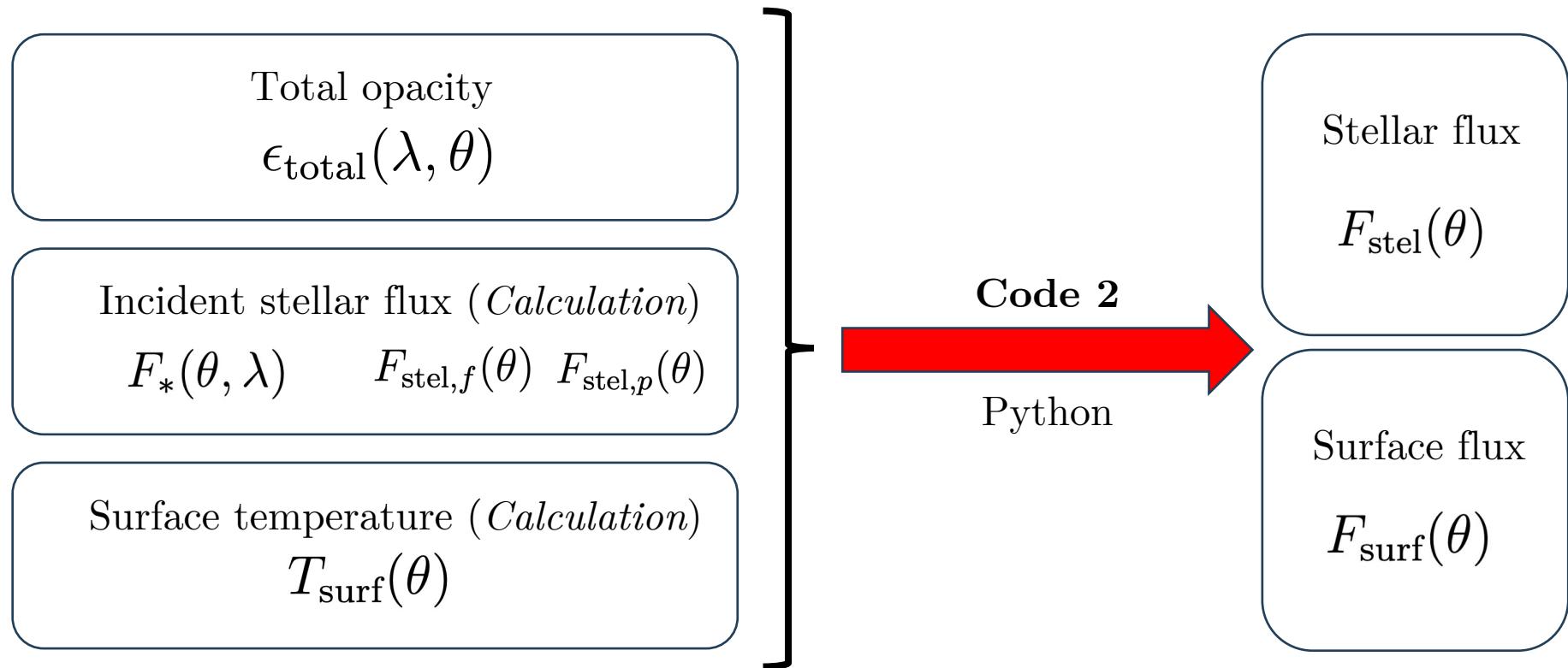
# IV. METHODOLOGY



# IV.II Total opacity



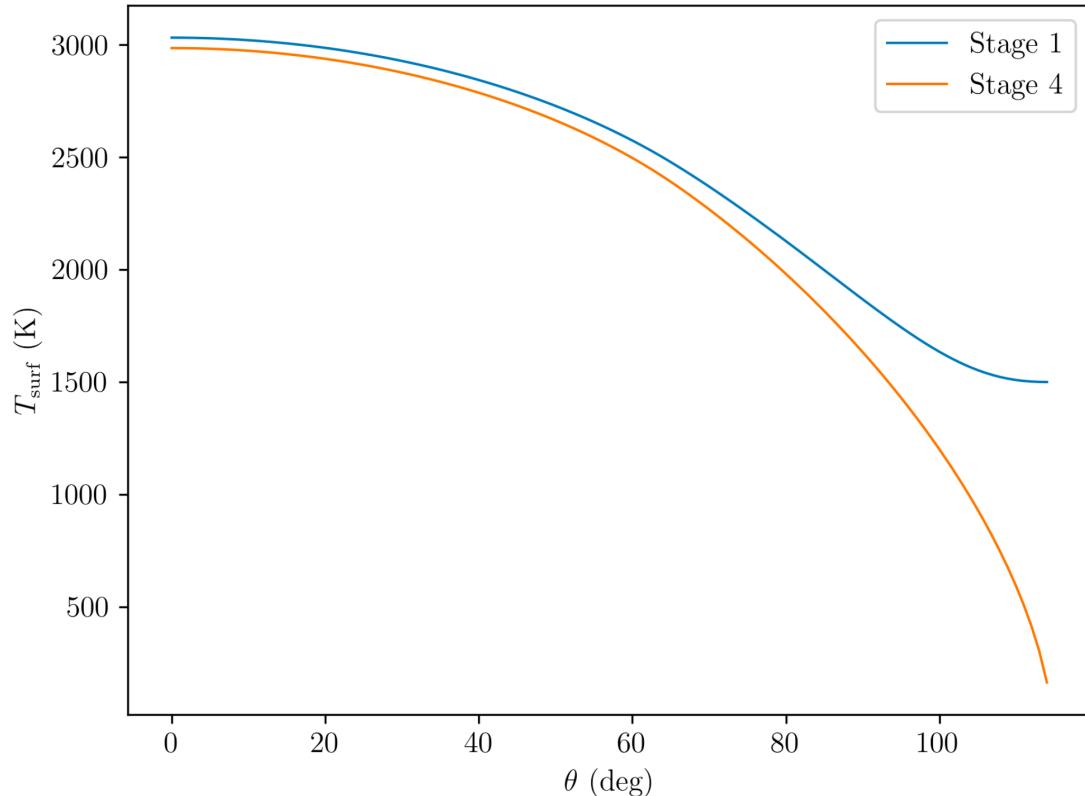
# IV.III Stellar and surface flux



# V. RESULTS



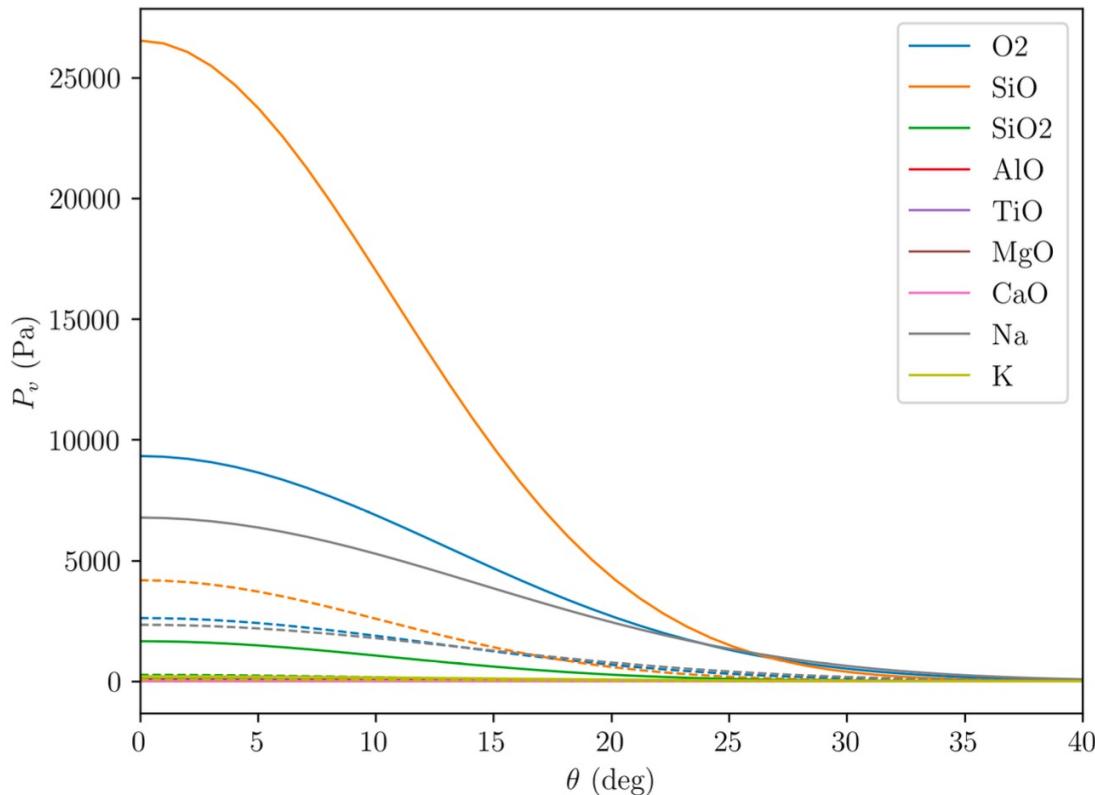
# V.I Surface temperature



**Stage 1:**  $T_s(0) = 3032 \text{ K}$

**Stage 4:**  $T_s(0) = 2986 \text{ K}$

# V.II Partial vapor pressures



Solid lines: Stage 1

Dashed lines: Stage 4

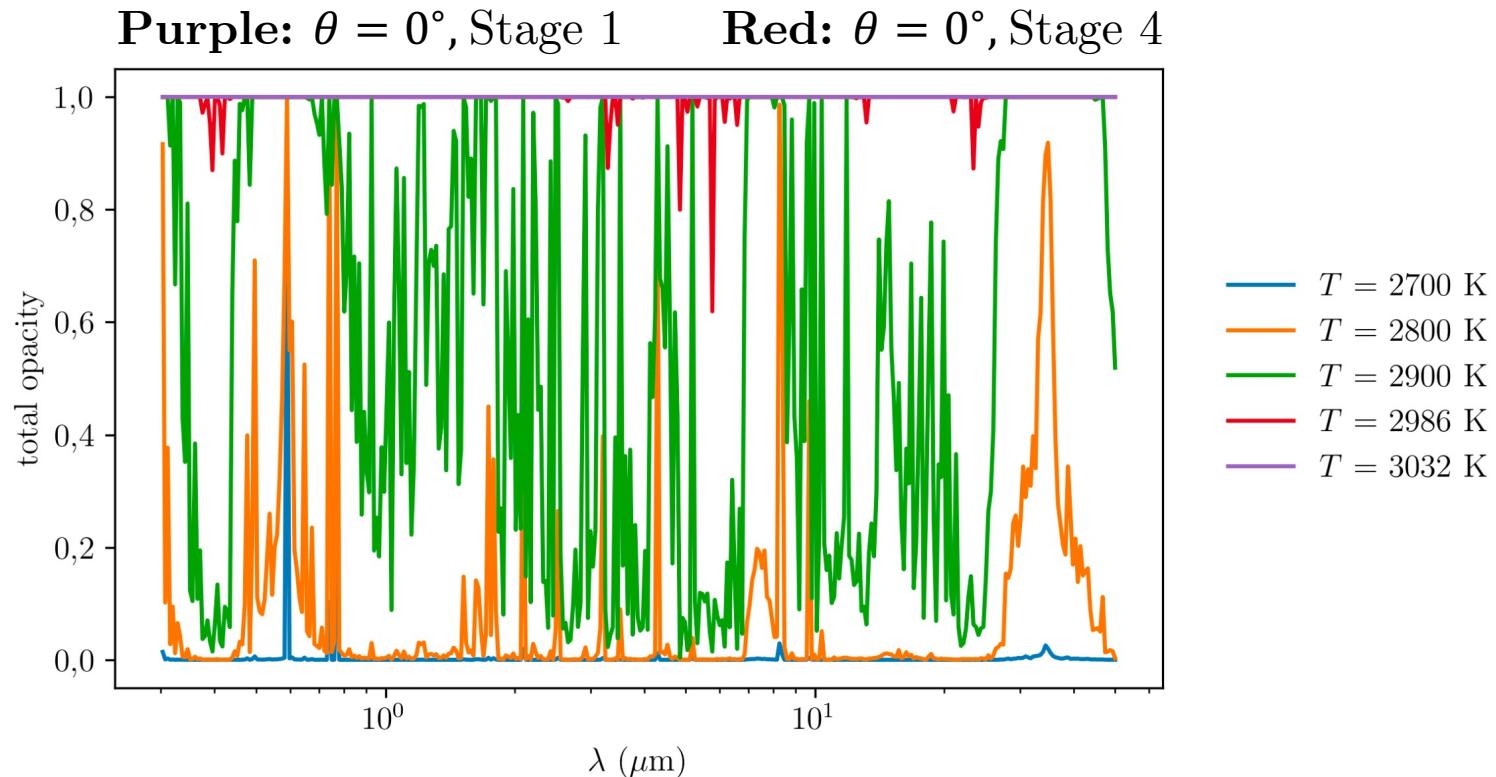
Same  $T_{\text{surf}}$  for both stages

Different magma composition

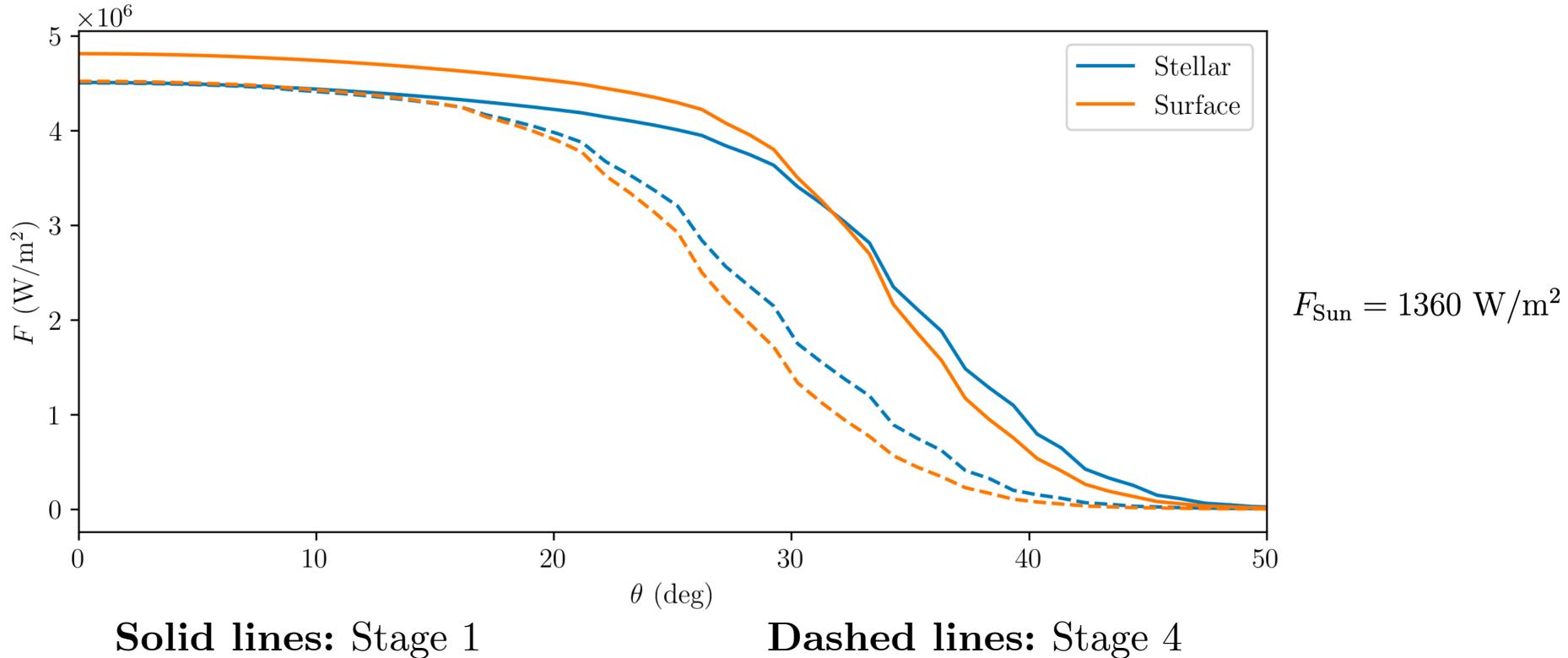


$\Delta P_v$  is negligible

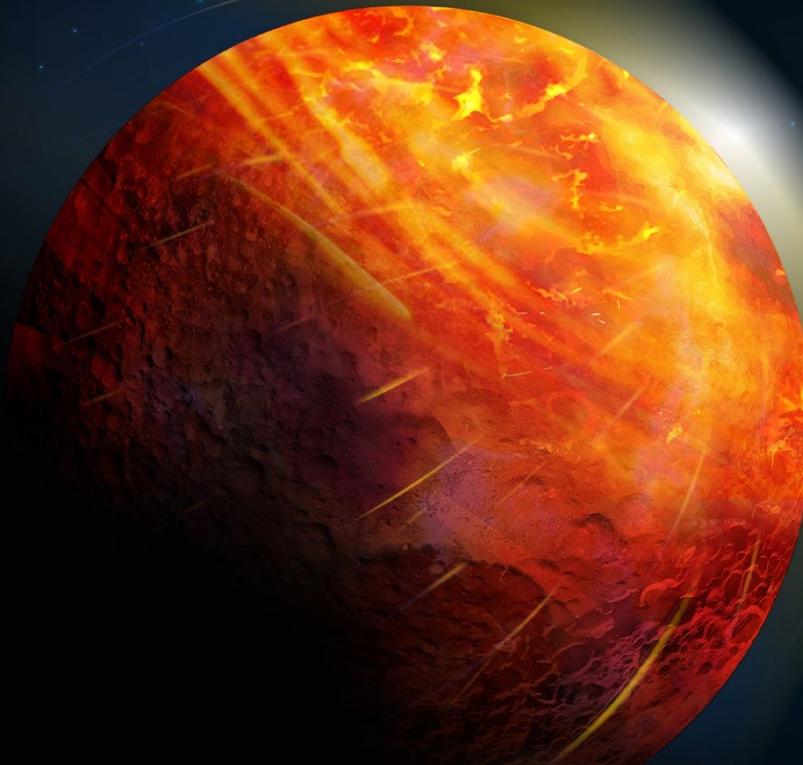
# V.III Total opacity



# V.IV Stellar and surface flux



# VI. CONCLUSIONS



# VI: CONCLUSIONS



- Hypothesis partially confirmed by results
- Magma ocean composition has limited impact
- Surface temperatures play a key role
- All objectives achieved – support Dr. Nguyen

*Artistic rendering (AI generated)*

# VI: CONCLUSIONS



## STAGE 1

- Higher total opacity
- Increased total pressure
- More extended atmosphere
- Greater flux absorption by the atmosphere

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# Thank you for your attention!

