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

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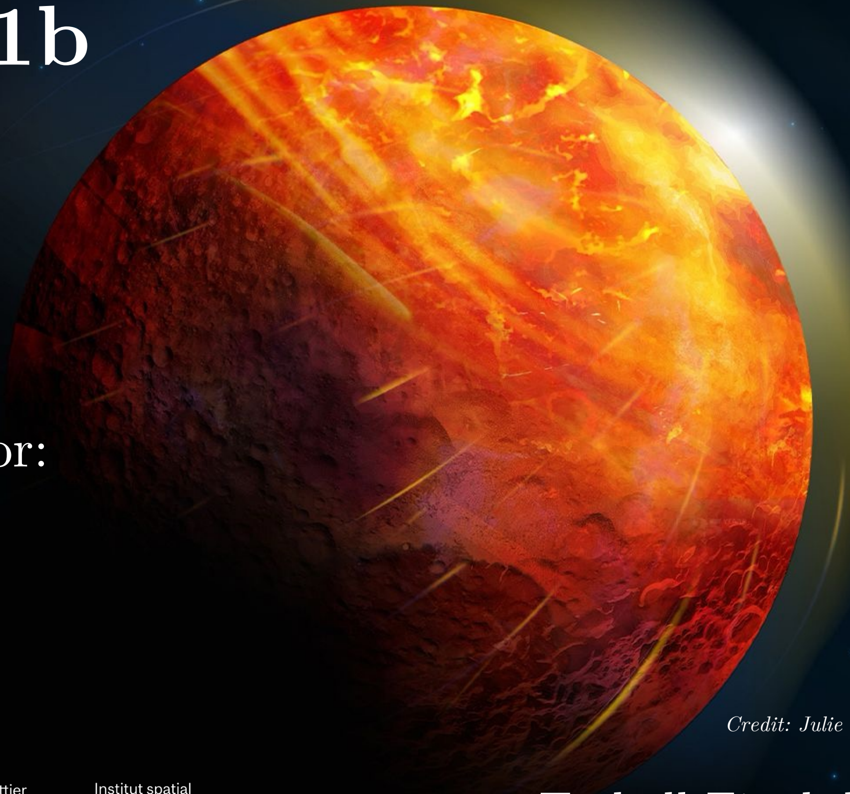


Credit: Julie Roussy, McGill Graphic Design

UAB Universitat Autònoma de Barcelona
McGill
TSI Trottier Space Institute at McGill
Institut spatial Trottier de McGill

Treball Final de Grau en Física

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

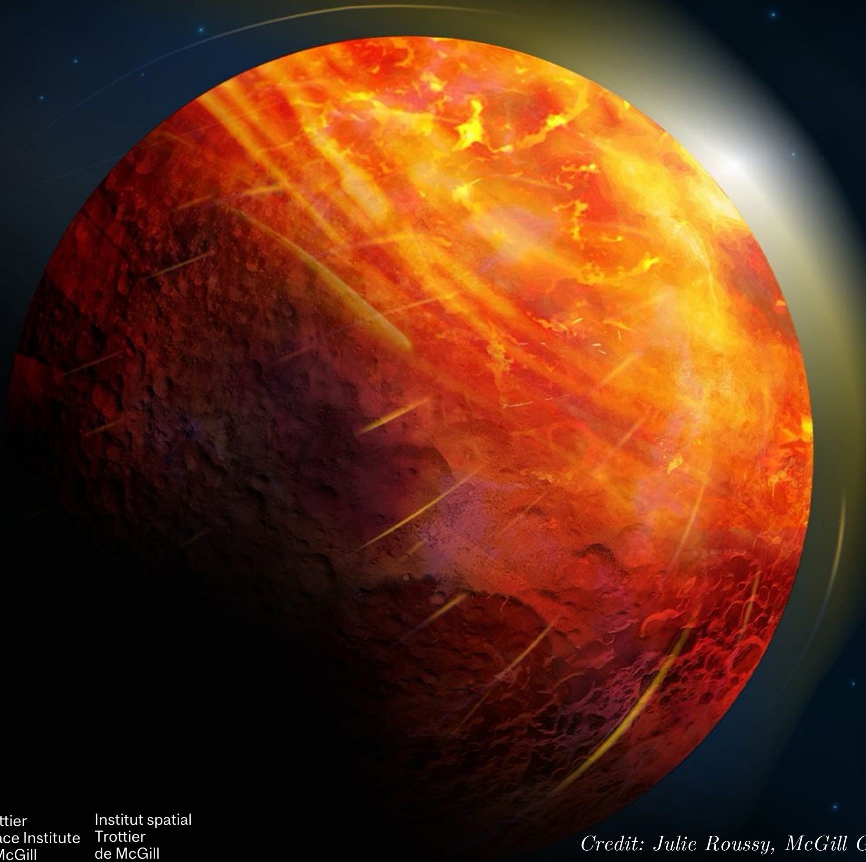
- Atmosphere collapses through rock rain before nightside

Artistic rendering (AI generated)

Index

Credit: Geoffrey Marchal

I. MOTIVATION



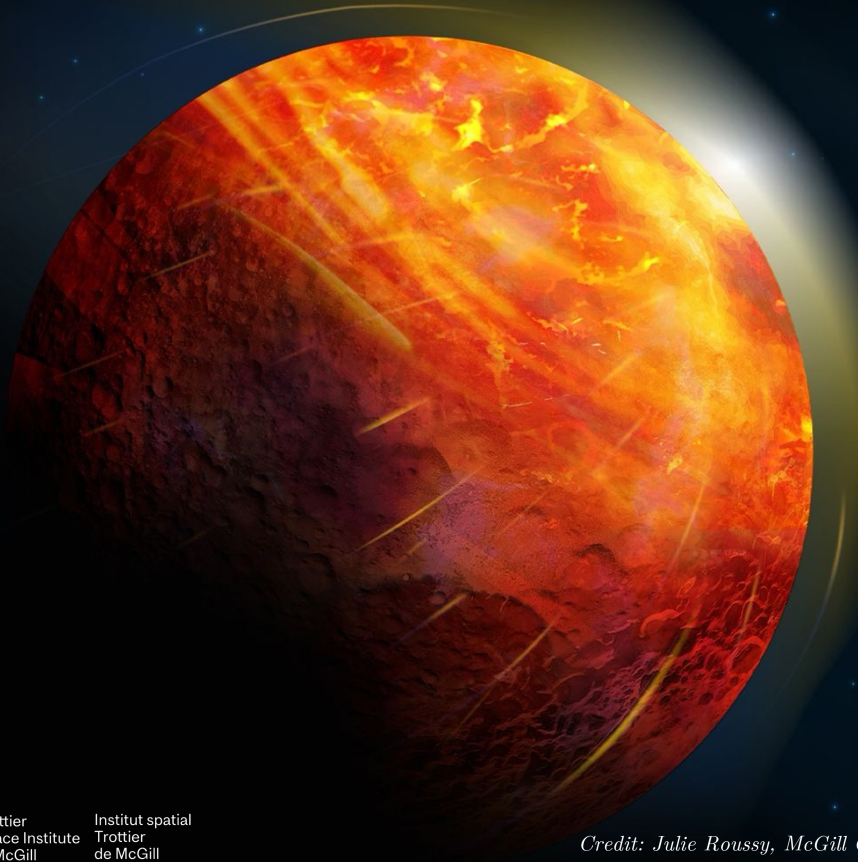
Credit: Julie Roussy, McGill Graphic Design

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



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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

Artistic rendering (AI generated)

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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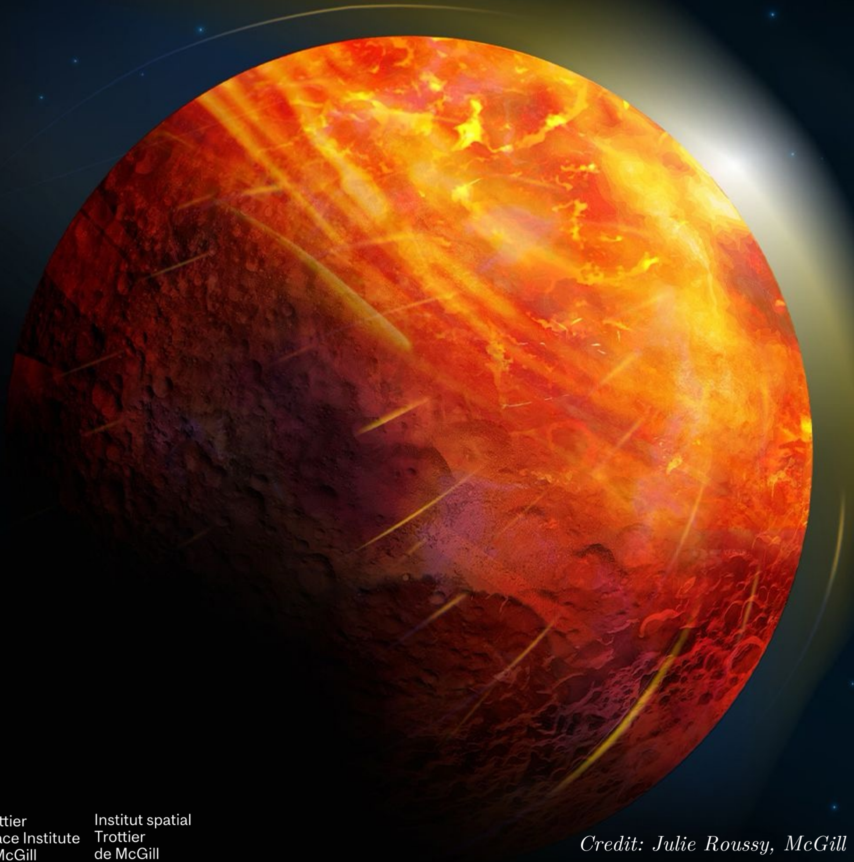
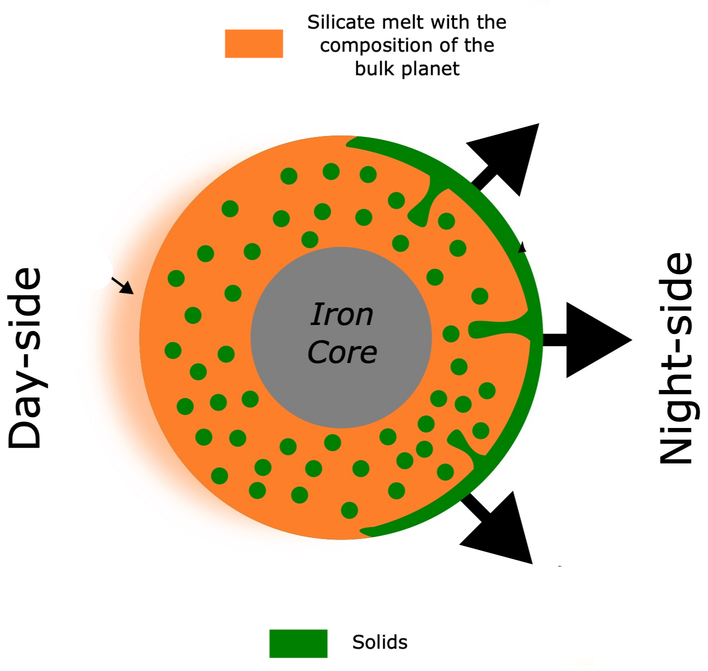
III. THEORETICAL BACKGROUND



Credit: Julie Roussy, McGill Graphic Design

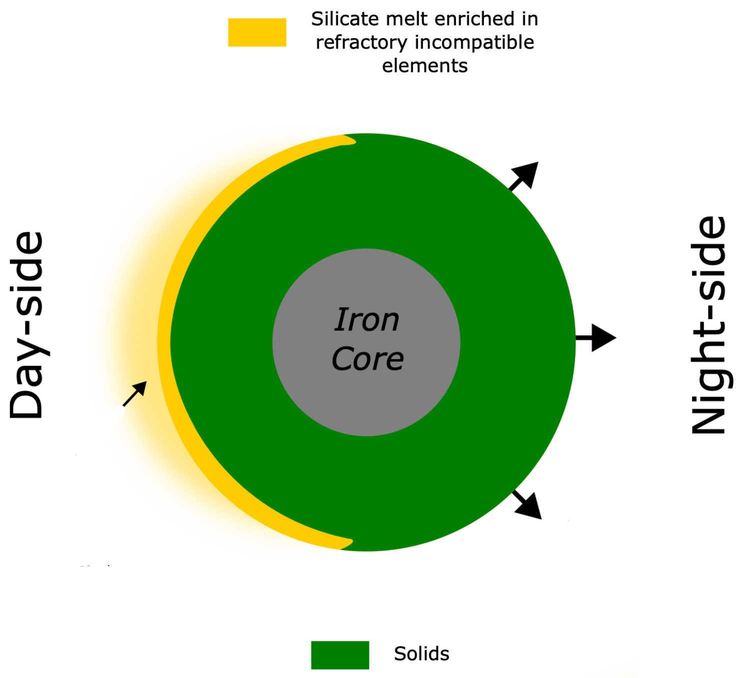
STAGE 1/GMO

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



Credit: Dr. Boukaré

III.I Evolutionary stages of a lava planet

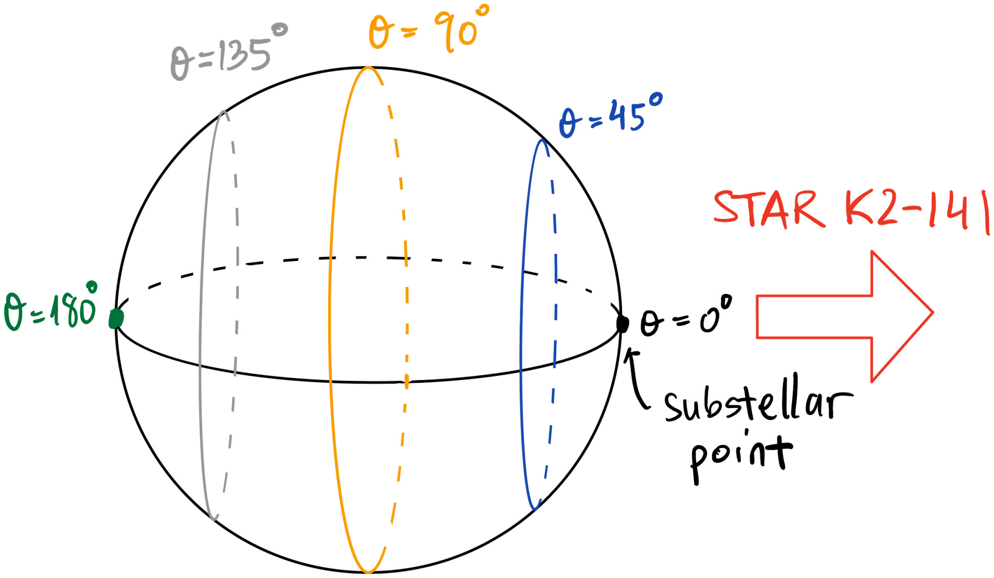


Credit: Dr. Boukaré

STAGE 4/SMO

- **Shallow magma ocean on dayside**
- **Maintained through stellar radiation**
- **Dynamically inactive**
- **Composition:** FeO, SiO, SiO_2

- **Co-latitude / angular distance from substellar point $\boldsymbol{\theta}$**



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

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

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

$$\theta_f = (\mathbf{64,37} \pm \mathbf{0,81})^\circ \qquad \theta_d = (\mathbf{114,54} \pm \mathbf{0,79})^\circ$$

Artistic rendering (AI generated)

III.IV Incident stellar flux

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

$T_* = (4,57 \pm 0,10) \times 10^3$ 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!

Artistic rendering (AI generated)

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

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

- **Total opacity at co-latitude $\boldsymbol{\theta}$:**

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

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

III.VII Radiative transfer formulation

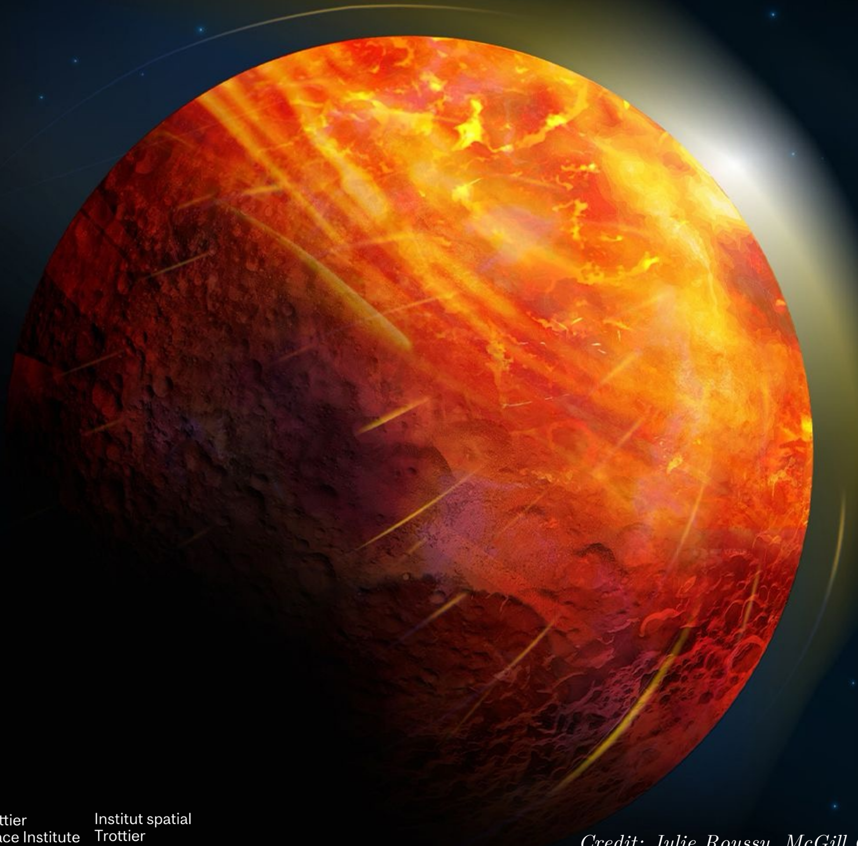
- **Stellar flux absorbed by the atmosphere at co-latitude $\boldsymbol{\theta}$:**

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

- **Surface flux absorbed by the atmosphere at co-latitude $\boldsymbol{\theta}$:**

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

IV. METHODOLOGY



Credit: Julie Roussy, McGill Graphic Design

IV.II Total opacity

Absorption cross section (*ExoMol*)

$$x_i(\lambda, P_{\text{atm}}, T_{\text{atm}}).$$

Partial vapor pressures (*Supervisor*)

$$P_i(T_{\text{surf}})$$

Surface temperature (*Calculation*)

$$T_{\text{surf}}(\theta)$$

Code 1

Python

Total opacity

$$\epsilon_{\text{total}}(\lambda, \theta)$$

IV.III Stellar and surface flux

Total opacity

$\epsilon_{\text{total}}(\lambda, \theta)$

Incident stellar flux (*Calculation*)

$F_*(\theta, \lambda)$ $F_{\text{stel},f}(\theta)$ $F_{\text{stel},p}(\theta)$

Surface temperature (*Calculation*)

$T_{\text{surf}}(\theta)$

Code 2

Python

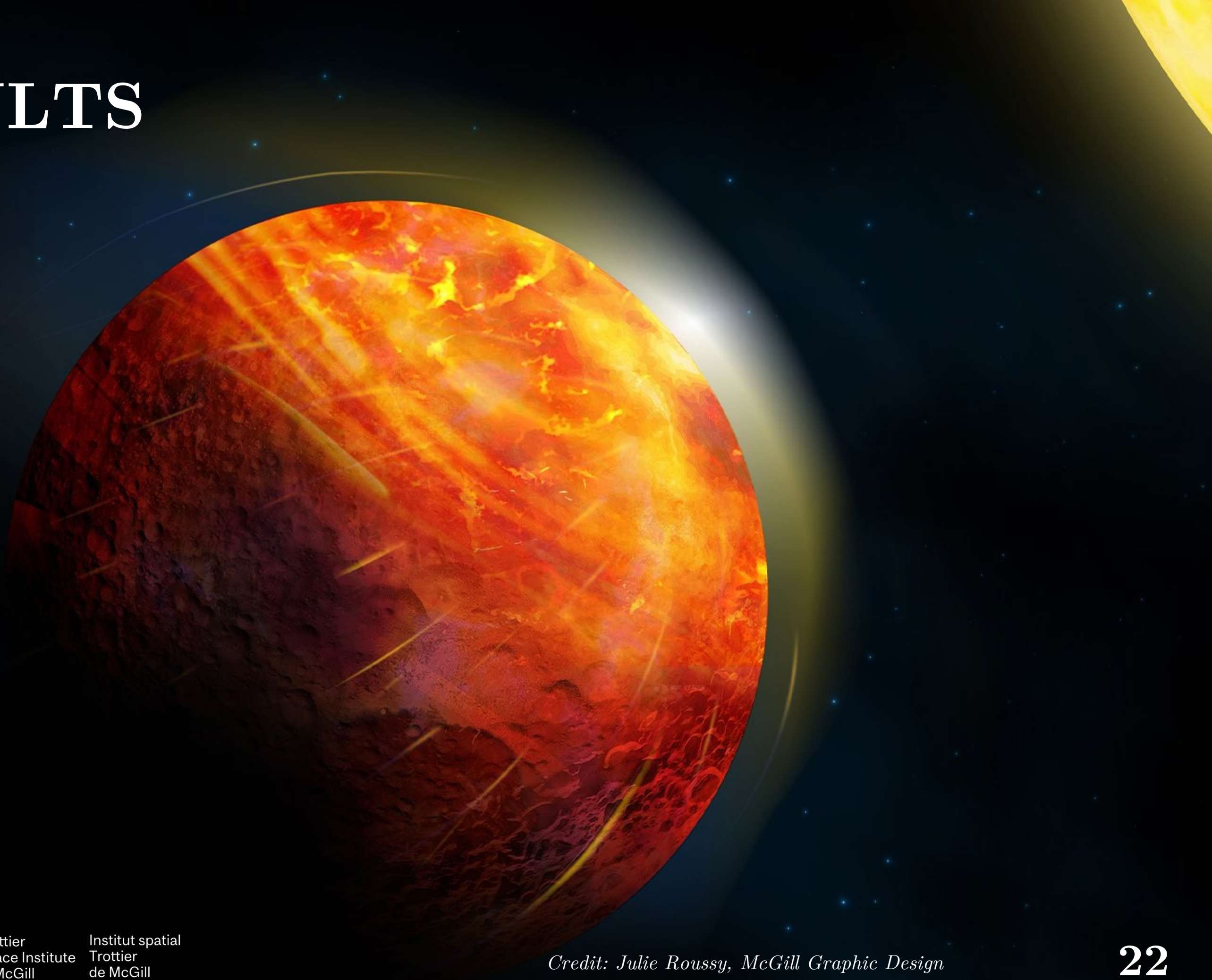
Stellar flux

$F_{\text{stel}}(\theta)$

Surface flux

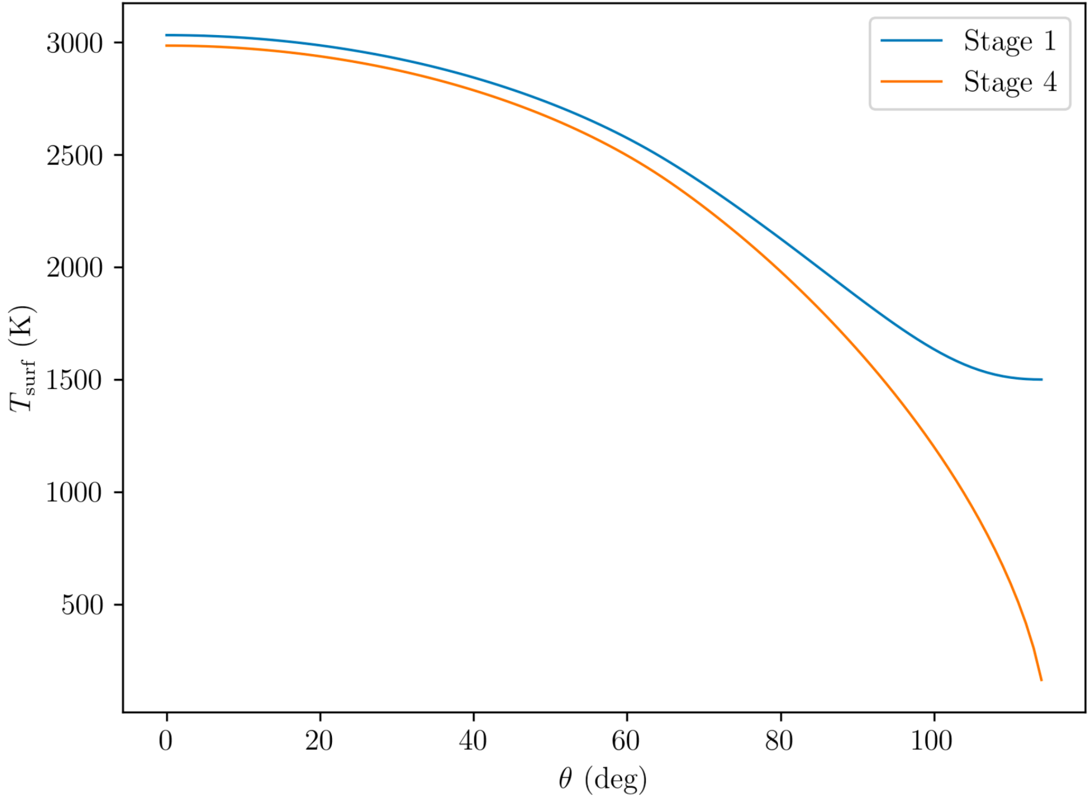
$F_{\text{surf}}(\theta)$

V. RESULTS



Credit: *Julie Roussy, McGill Graphic Design*

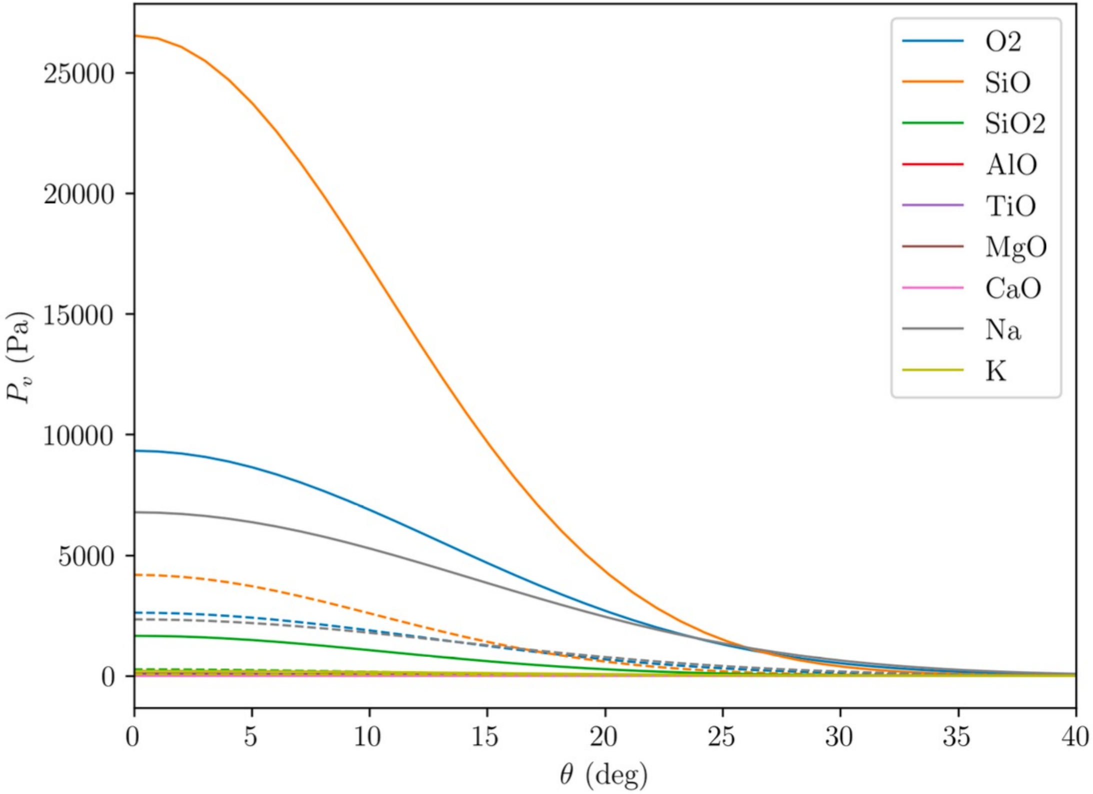
V.I Surface temperature



Stage 1: $T_s(0) = 3032\,K$

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

V.II Partial vapor pressures



Solid lines: Stage 1

Dashed lines: Stage 4

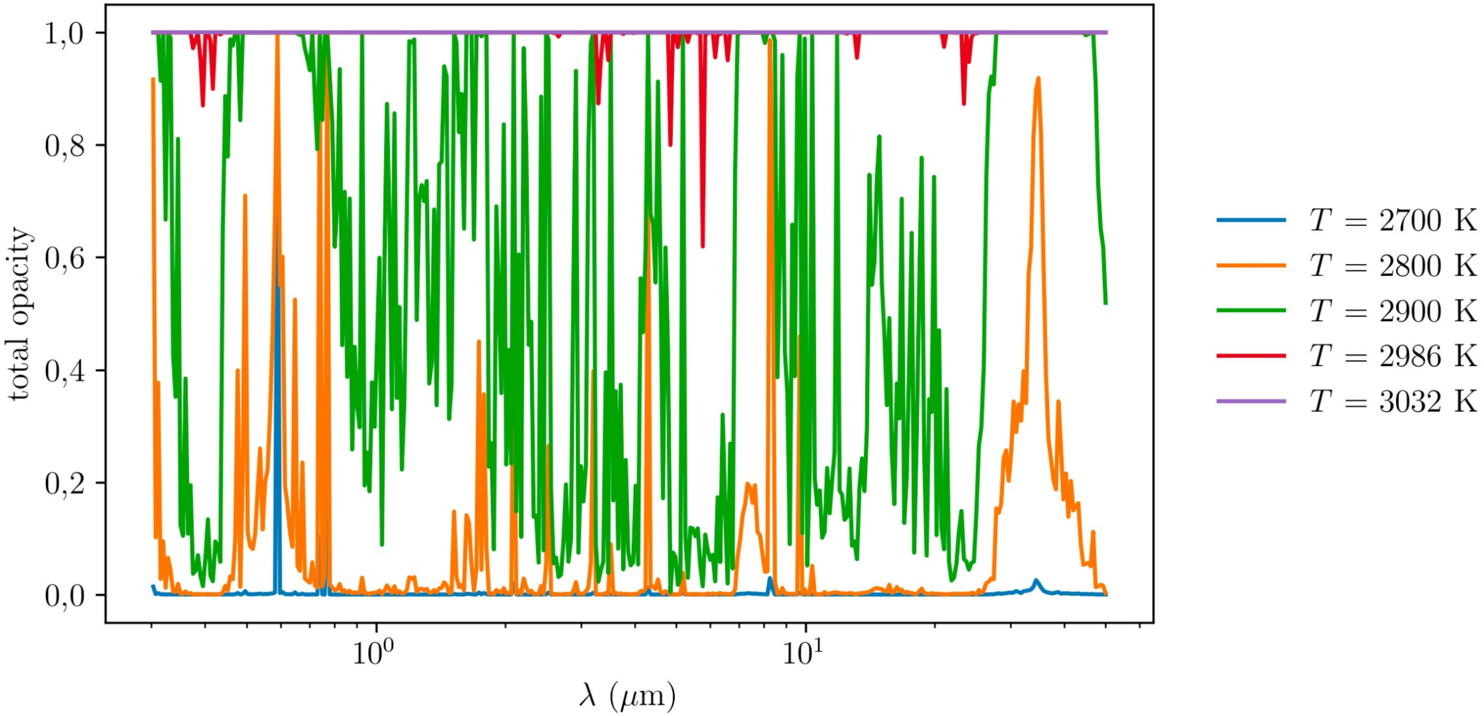
Same T_{surf} for both stages

Different magma composition

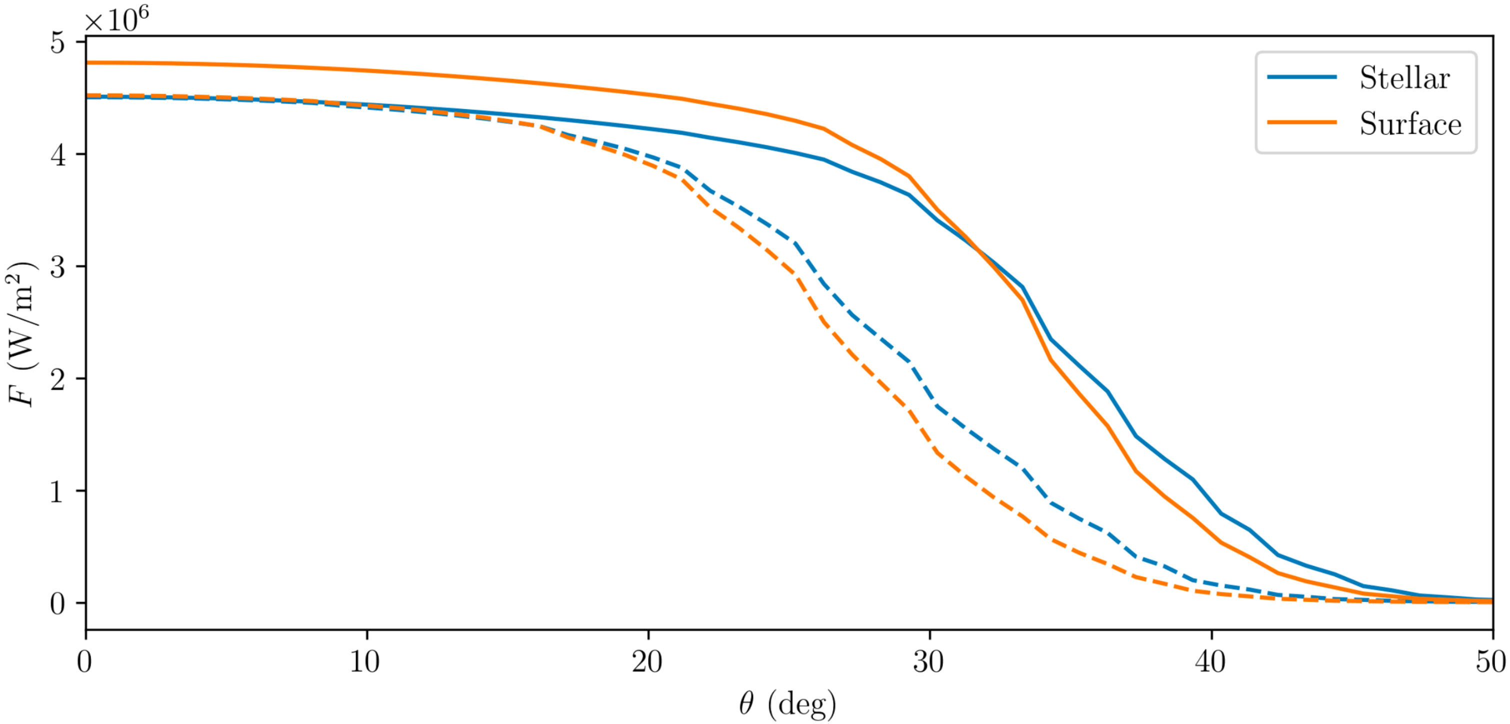
ΔP_v is negligible

V.III Total opacity

Purple: $\theta = 0°$, Stage 1 **Red:** $\theta = 0°$, Stage 4



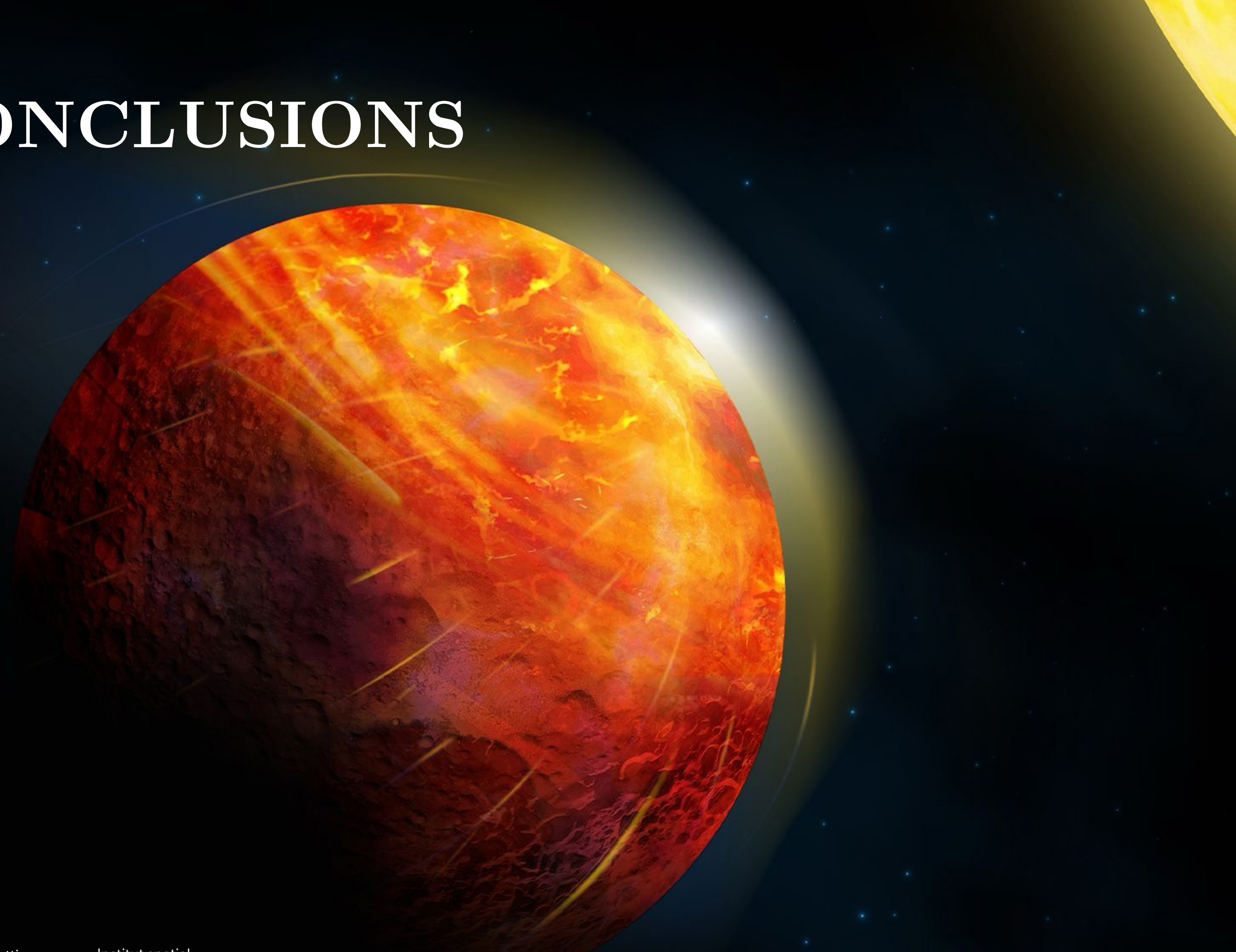
V.IV Stellar and surface flux



$F_{\mathrm{Sun}} = 1360$ W/m^2

Solid lines: Stage 1 **Dashed lines:** Stage 4

VI. CONCLUSIONS



Credit: Julie Roussy, McGill Graphic Design

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)

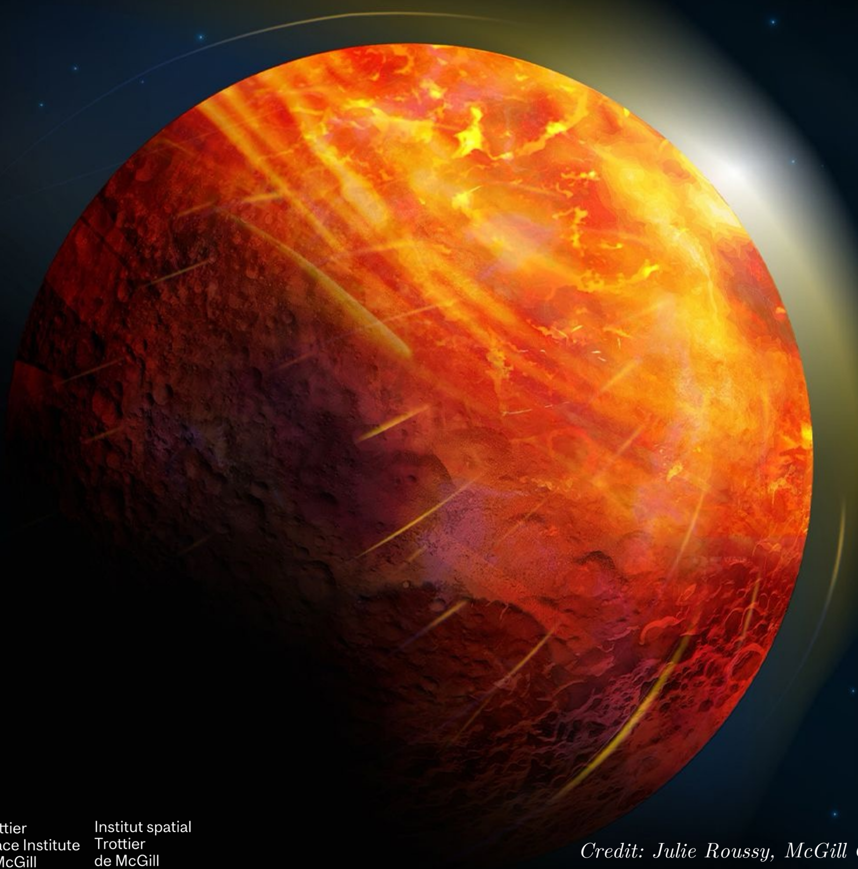
VI: CONCLUSIONS

STAGE 1

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

Artistic rendering (AI generated)

Thank you for your attention!



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