THERMAL EVOLUTION OF TRAPPIST-1 PLANETS VIA MULTILAYER TIDAL DISSIPATION MODELS

We model TRAPPIST-1planets with multilayer tidal dissipation models to track how interior structure and temperature-dependent viscosity shape long-term thermal evolution. Our results show that tidal heating dominates the inner planets' energy budgets, can trigger runaway melting, and accelerates atmospheric outgassing, linking interior dynamics to future atmospheric observations.

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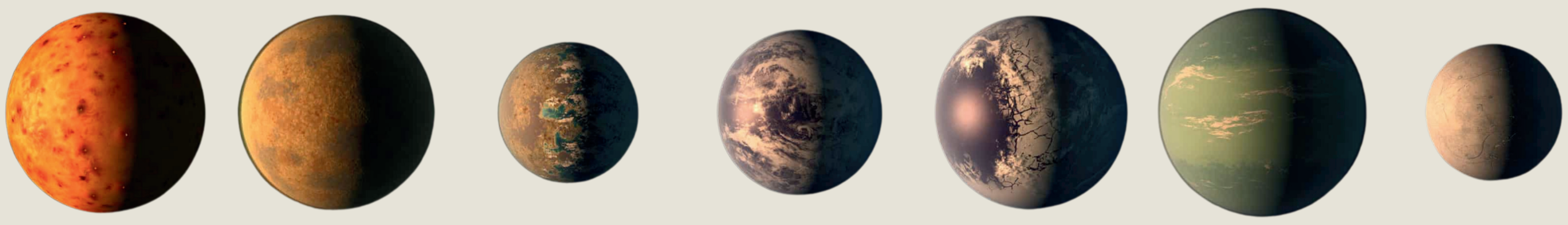

INTRODUCTION

- TRAPPIST-1 hosts seven Earth-sized planets orbiting an M-dwarf star.
- Tidal heating could be the primary source of energy driving geological activities.
- Homogeneous models oversimplify interiors and underestimate tidal heating[1].
- We adopt multilayer models to capture complex, temperature-dependent dissipation and its role in long-term thermal evolution.

METHODOLOGY

- **Interior Models**: Bayesian inversion yields mass fractions of an iron core, a silicate mantle, and optional ice layers[2,3], using updated equations of state[4-6].
- **Tidal Dissipation**: Love numbers calculated for multilayer structures using Maxwell/Andrade rheologies[7-9], including a parameterization for the effects of partial melt[10,11].
- **2D Mantle Convection (CHIC)**: Allows for detailed investigation of the 2D spatial distribution of tidal dissipation and its effect on mantle dynamics, melt production, and volatile transport, directly linking the interior to atmospheric evolution[12].
- **Case Studies**: Hot inner planet **TRAPPIST-1b** and moderately heated **TRAPPIST-1d**.

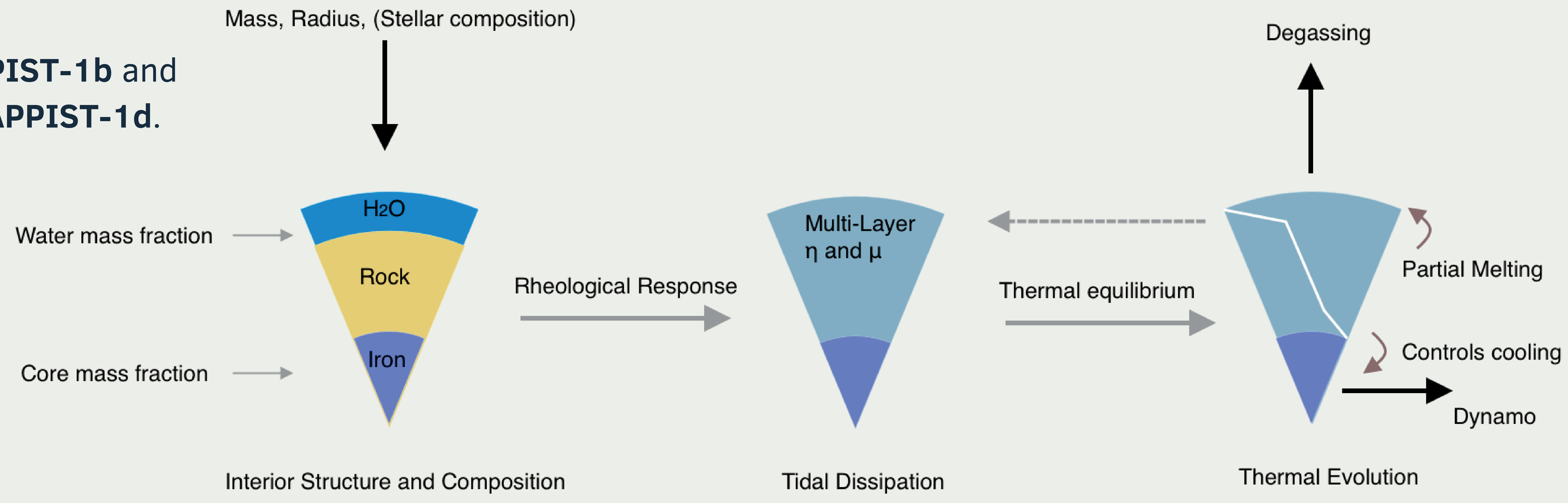

Figure1. This schematic illustrates the research methodology.

RADIAL AND LAYERED DISSIPATION PATTERNS

- Dissipation varies **strongly** with depth(Figure 2 and 3a).
- Peaks often occur at the **core–mantle boundary** and in **ice layers** (depending on rheology).
- Liquid layers can decouple the deep interior, suppressing inner dissipation and enhancing outer dissipation.
- These multilayer results may differ by **2-3 orders of magnitude** from homogeneous models

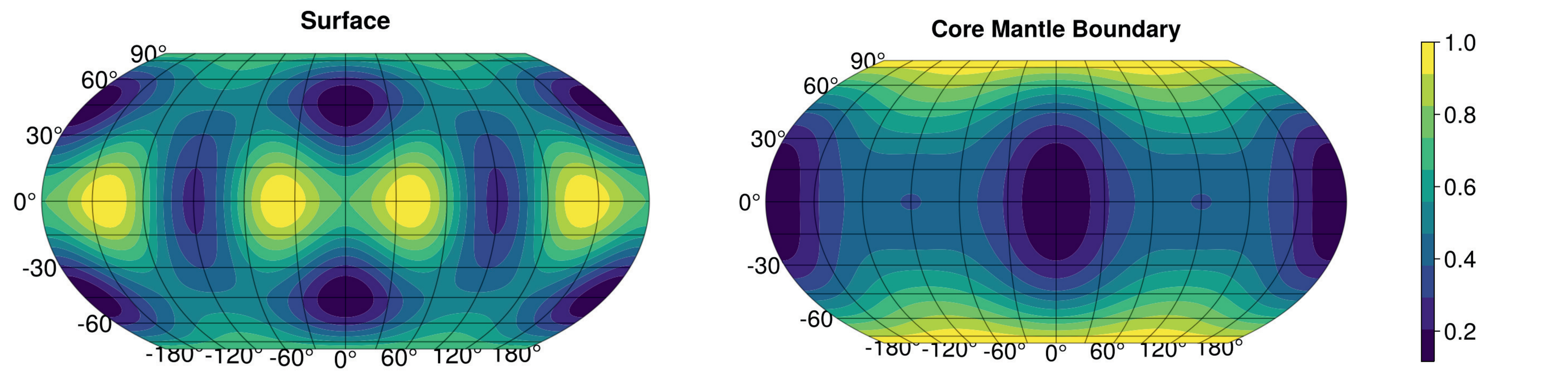

Figure2. Tidal dissipation patterns for TRAPPIST-1b at the surface and the core-mantle boundary

A TEMPERATURE-VISCOSITY FEEDBACK DOMINATES THERMAL EVOLUTION

Our models reveal a critical positive feedback mechanism, especially in the inner, tidally heated planets like TRAPPIST-1b.

- **Higher temperatures** significantly reduce mantle viscosity and expand partially molten regions (Figure 3).
- This **drop in viscosity** enhances the efficiency of tidal dissipation, generating even more heat.
- This feedback loop can lead to **runaway melting** if heat transport is limited, potentially resulting in extensive magma layers and a dramatically different thermal state than previously assumed.

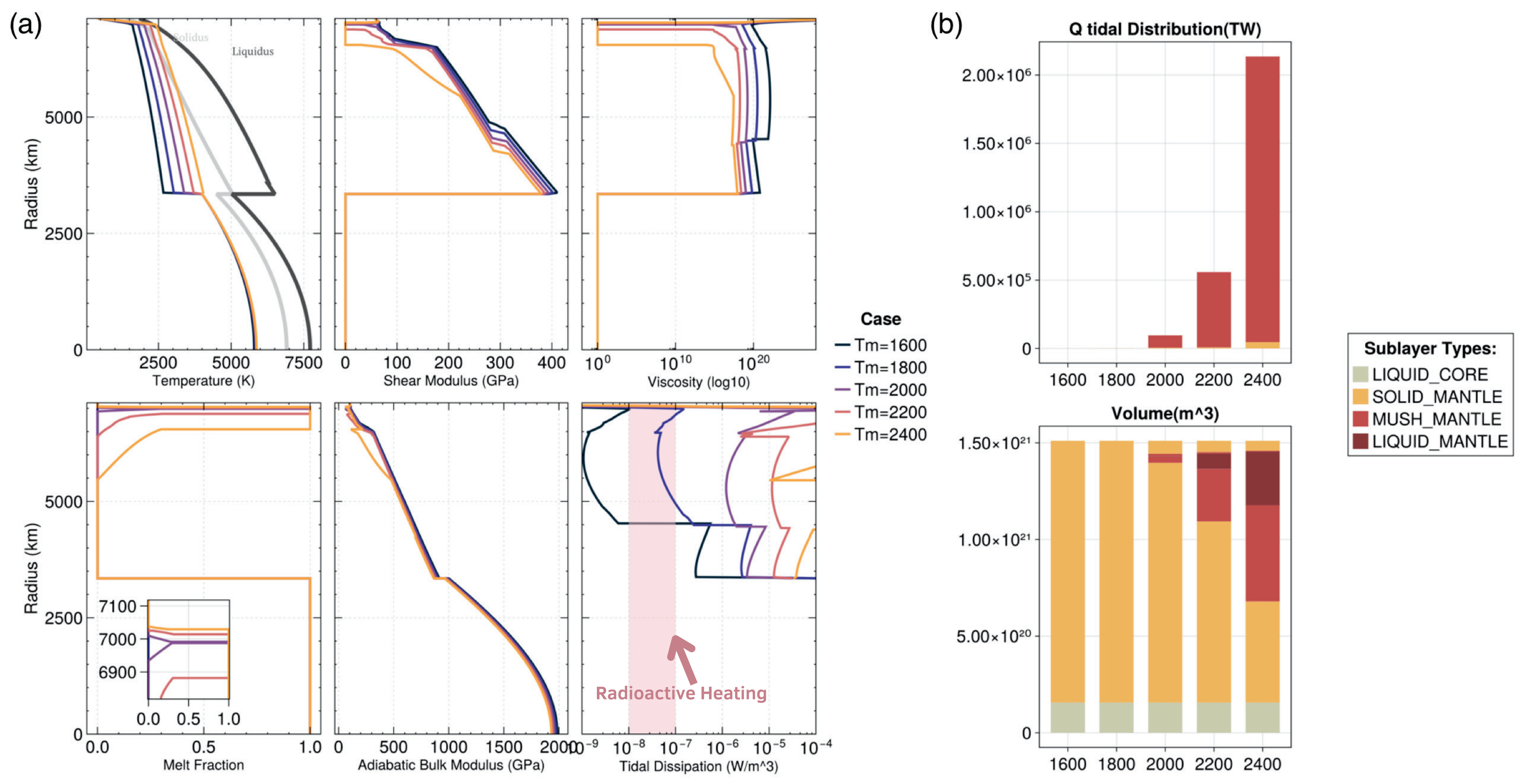

Figure3. The effect of mantle temperature on TRAPPIST-1b's interior and tidal response. (a) Radial profiles show that higher temperatures create expanded, low-viscosity partially molten layers. (b) This leads to a dramatic increase in total tidal dissipation power, dominated by heating within these mush layers.

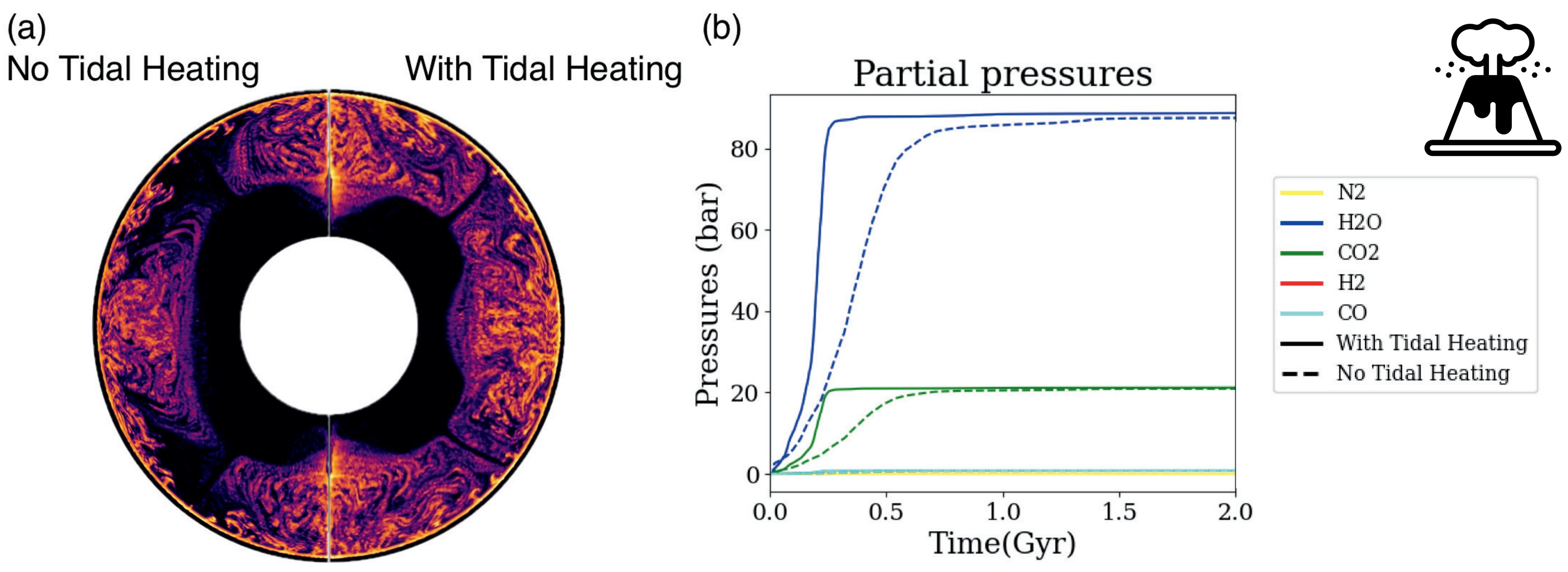

Figure4. (a) Mantle volatile depletion in TRAPPIST-1d after 1 Gyr of evolution, comparing models without tidal heating (left) and with tidal heating (right). Yellow-pink regions indicate higher levels of volatile depletion. (b) Evolution of atmospheric partial pressures over time (0-2 Gyr) for N_2, H_2O, CO_2, H_2, and CO.

TIDAL HEATING ACCELERATES ATMOSPHERIC OUTGASSING

The intense internal heating has profound consequences for the development of planetary atmospheres.

- **Enhanced Volatile Cycling**: Increased temperatures and expanded melting zones facilitate a more efficient extraction of volatiles (like H_2O and CO_2) from the planet's mantle. As shown in Figure 4, tidal heating significantly accelerates mantle volatile depletion during the first ~1 Gyr of evolution.
- **Secondary atmosphere build-up:** Planets with strong tidal heating develop substantial secondary atmospheres much faster than those without, although the final atmospheric pressure may converge over longer timescales.

CONCLUSION

- Tidal heating is the **dominant energy source** for inner TRAPPIST-1 planets, exceeding radiogenic heating.
- **Multilayer** interior structure and **temperature-dependent rheology** are essential to accuratsely model heating and melting.
- A strong **temperature-viscosity feedback** loop is the core mechanism controlling the planets' internal thermal state, capable of inducing runaway melting and forming molten regions.
- The planet's interior evolution is directly **coupled to its atmospheric evolution**. Tidal heating accelerates the outgassing process, providing a crucial link between geophysics and the potential for future atmospheric characterization with space missions.

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