XMS3GU050 - EARTH AND PLANETARY INTERIORS REPORT
Interior dynamics – Mars

Demur Merkviladze

Introduction

The goal of this report is to address the thermal structure and interior dynamics of Mars. In this practical, we calculate the temperature profile inside Mars' crust and mantle due to the heat generated by radioactive decay, and assess the evolution of the planet's cooling history.

Radioactive Heating

The radioactive heating within Mars' mantle and crust is calculated using the following equation:

$$H(t) = H_0 e^{-\lambda t} \tag{1}$$

where $H_0 = 2 \times 10^{-11}\,\mathrm{W\,kg^{-1}}$ is the initial heat production rate and $\lambda = 4.39 \times 10^{-4}\,\mathrm{Myr^{-1}}$ is the decay constant. We assume that the main source of heating is the decay of the radioactive elements The time $t = 4500\,\mathrm{Myr}$ represents the current age of Mars.

The calculated radioactive heating rate at present is:

$$H = 2.77 \times 10^{-12}\,\mathrm{W/kg} \tag{2}$$

Convective Temperatures and Viscosity Calculations

For convective temperatures in the range of 1400 K to 1800 K, we calculate the temperature differences and viscosity.

The change in temperature due to viscosity ΔT_η is given by:

$$\Delta T_\eta = \frac{R_g T^2}{Q} \tag{3}$$

where $R_g = 8.314\,\mathrm{J/molK}$, $Q = 250 \times 10^3\,\mathrm{J/mol}$, and T is the convective temperature.

The temperature difference across the thermal boundary layer ΔT_{TBL} is:

$$\Delta T_{\text{TBL}} = 2.23 \Delta T_\eta \tag{4}$$

The temperature at the stagnant lid T_{sl} is:

$$T_{\text{sl}} = T - \Delta T_{\text{TBL}} \tag{5}$$

The viscosity η as a function of temperature is given by:

$$\eta = \eta_{\text{ref}} \exp\left(\frac{Q}{R_g}\left(\frac{1}{1600} - \frac{1}{T}\right)\right) \tag{6}$$

where $\eta_{\text{ref}} = 3.1 \times 10^{21}\,\text{Pa}\,\text{s}$.

Rayleigh Number and Boundary Layer Depth

The Rayleigh number Ra is calculated using:

$$\text{Ra} = \frac{g\alpha\Delta T d^3}{\kappa\eta} \tag{7}$$

where:

- $g = 3.73\,\text{m/s}^2$ is the gravitational acceleration,
- $\alpha = 3 \times 10^{-5}\,\text{K}^{-1}$ is the thermal expansion coefficient,
- ΔT is the temperature difference across the boundary layer,
- d is the thickness of the boundary layer,
- $\kappa = \frac{k}{\rho_m C_p} = 3.01 \times 10^{-7}\,\text{m}^2/\text{s}$ is the thermal diffusivity,
- η is the viscosity.

The depth of the boundary layer d is computed from the thermal boundary layer Rayleigh number Ra_{TBL}:

$$d = \left(\frac{\text{Ra}_{\text{TBL}}\kappa\eta}{\alpha\rho_m T_{\text{sl}}}\right)^{1/3} \tag{8}$$

where $\text{Ra}_{\text{TBL}} = 70$, $\alpha = 3 \times 10^{-5}\,\text{K}^{-1}$, and $\rho_m = 3448\,\text{kg/m}^3$.

The temperature gradient and stagnant lid thickness are calculated as follows:

$$\text{Gradient} = \frac{\Delta T_{\text{TBL}}}{d} \tag{9}$$

The stagnant lid thickness D_{sl} is:

$$D_{\text{sl}} = \frac{T_{\text{sl}} - T_c}{\text{Gradient}} \tag{10}$$

where T_c is the surface temperature.

The depth of the boundary layer $D_{\mathrm{d+sl}}$ is:

$$D_{\mathrm{d+sl}} = D_{\mathrm{sl}} + d \tag{11}$$

The following results were obtained for different convective temperatures:

T (K)	ΔT_η (K)	ΔT_{TBL} (K)	T_{sl} (K)	η (Pa·s)	d (km)	$D_{\mathrm{d+sl}}$ (km)
1400	65.19	145.36	1254.64	4.54×10^{22}	262.39	2148.03
1500	74.83	166.87	1333.13	1.09×10^{22}	159.55	1233.38
1600	85.14	189.86	1410.14	3.10×10^{21}	103.13	755.04
1700	96.12	214.34	1485.66	1.03×10^{21}	70.12	487.42
1800	107.76	240.30	1559.70	3.84×10^{20}	49.72	328.98

Table 1: Calculated values for different convective temperatures, including temperature change due to viscosity, temperature difference across TBL, temperature at the stagnant lid, viscosity, thickness of boundary layer, depth of boundary layer.

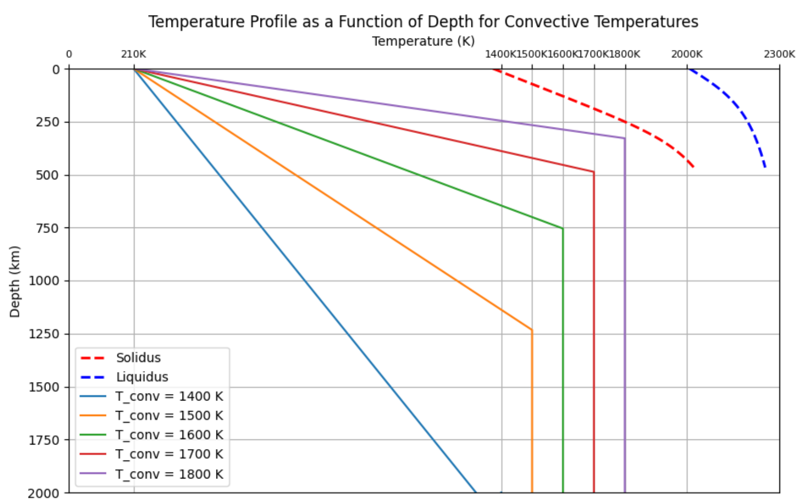

Figure 1: Temperature profile for a series of convective temperatures as a function of depth, with liquidus and solidus of silicates.

Pressure from Solidus Temperature and Liquidus Temperature from Pressure

The pressure P as a function of the solidus temperature T_s is given by the equation:

$$P = \frac{T_s - 1100}{136} + 4.968 \times 10^{-4} e^{0.012(T_s - 1100)} \tag{12}$$

where P is in GPa and T_s is in degrees Celsius.

The liquidus temperature T_{liq} as a function of pressure P is given by:

$$T_{\text{liq}} = 1736.2 + 4.343P + 180 \arctan\left(\frac{P}{2.2169}\right) \tag{13}$$

where T_{liq} is in degrees Celsius and P is in GPa.

For a maximum pressure of 6 GPa, the depth and liquidus temperature are:

- $depth = 467m$
- $T_{\text{liq}} = 2254K$

Heat Flux and Urey Number

To assess the cooling rate of Mars, we calculate the heat flux and compare it with the internal heating. The heat flux q is derived from the convective properties of the mantle, and the Urey number U is calculated as:

$$U = \frac{H_{\text{internal}}}{q_{\text{surface}}} \tag{14}$$

where H_{internal} is the internal heat production rate and q_{surface} is the surface heat flux.

Convective Temperature	**1400 K**	**1500 K**	**1600 K**	**1700 K**	**1800 K**
Heat Flux (mW/m^2)	1.66	3.14	5.52	9.17	14.50
Internal Heat Production (mW/m^2)	2.51	1.53	0.99	0.67	0.48
Urey Number	1.510	0.486	0.179	0.073	0.033

Table 2: Calculated values for different convective temperatures, showing Heat Flux, Internal Heat Production, and Urey Number.

Proposed Scenario: From Magma Ocean to Present-Day Interior Structure of Mars

1. Magma Ocean Phase (4.5 billion years ago): After its formation, Mars likely underwent a period dominated by a global magma ocean due to significant heat from accretion and core formation. This molten layer began to crystallize as the planet radiated heat into space, leading to the differentiation of the crust, mantle, and core. The crust would form first from lighter minerals, with denser, solidified silicates settling in the mantle.

2. Early Cooling and Crust Formation (4.5 to 4 billion years ago): As the magma ocean solidified, Mars experienced rapid cooling. Radioactive decay of short-lived isotopes contributed to early heat production, keeping parts of the mantle molten and driving convection. During this phase, Mars developed a thick, insulating crust, which limited mantle convection to deeper layers. This thick crust and reduced surface volcanism suggest early cooling and the formation of a strong stagnant lid.

3. Development of a Thick Stagnant Lid (4 billion years to 3 billion years ago): With time, the decay of radioactive isotopes decreased significantly, reducing internal heat production. The planet transitioned to a state dominated by a thick stagnant lid. Convective currents were largely constrained below this lid, which acted as an insulating layer, trapping heat within the mantle. This period likely witnessed limited tectonic activity and surface volcanism, a characteristic observed in Mars' ancient volcanic provinces.

4. Progressive Cooling and Reduced Heat Flux (3 billion years ago to present): As radioactive heating continued to decline, the Urey number decreased, suggesting that heat flux from the mantle to the surface has gradually surpassed internal heat generation. This trend led to further cooling and a thinner, more stable thermal boundary layer. The reduction in mantle convection has contributed to Mars' limited tectonic activity, creating a quiescent interior dominated by a stable, thick lithosphere.

5. Present-Day Interior Structure: Today, Mars' interior structure reflects a balance between residual heat from early planetary formation and low ongoing heat production. The current thermal boundary layer is relatively thin, and heat flux is insufficient to drive significant surface or tectonic activity, resulting in a cold, mostly solid mantle. Mars' thick, stagnant lithosphere limits further cooling and suggests an interior that has nearly reached thermal equilibrium.

Conclusion

The results of this study reveal a consistent cooling trend within Mars' interior, primarily due to the decreasing radioactive heat production over time. The calculations indicate that the depth and thickness of Mars' thermal boundary layer decrease significantly with increasing convective temperature, which suggests a transition from a thicker stagnant lid to a thinner, more dynamic layer at higher temperatures.

The calculated Urey numbers highlight Mars' low internal heat retention, particularly at higher convective temperatures where the Urey number drops below 0.1. This trend indicates that the heat flux from Mars' mantle to its surface exceeds the heat produced by radioactive decay, pointing to an interior that has cooled substantially over geological time.

These findings support the hypothesis that Mars has experienced extensive cooling since its formation, likely affecting its tectonic and volcanic activity. The study of Mars' thermal dynamics provides valuable insights into its geological evolution, helping to explain the limited tectonic activity observed on the planet today. Further analysis incorporating varying crustal compositions and mantle convection patterns could offer a more detailed picture of Mars' cooling history and its implications for planetary habitability and surface evolution.