Thermal evolution of an early magma ocean in interaction with the atmosphere


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Motivation

• Water condensation (Earth/Venus/Mars)?

• Cooling of magma ocean sets the initial conditions for tectonics regime and habitability conditions.

• Duration of the magma ocean phase on the three terrestrial planets? Sequential or continuous?

• Influence of volatile contents, distance to the Sun, radioactive heating

This parametric approach completes existing full 3-D convection numerical simulations.
Magma ocean: Thermal evolution model

Scheme of the solidifying magma ocean adapted from (Solomatov, 2000).

Abe, 1993
Magma ocean: Thermal evolution model

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Heat conservation

$$I \frac{dT_p}{dt} = \left[ R_p^2 F_s \right] + Q_r$$

$$F_s = F_{net}$$

Thermal convection

$$F_s = 0.089 \frac{k(T_p - T_s)}{l} Ra^n$$

$$Ra = \frac{\alpha g \Delta T l^3}{\kappa \nu}$$

n=1/3 to 1/5
Atmospheric model

- 1D radiative-convective model
- Massive H2O-CO2 atmosphere
- Includes:  
  . Convection in the troposphere  
  . Presence of water clouds  
  . Condensation of water vapour  
  . Pressure contribution of N2 gas  
- Thermal IR opacities computed using a k-correlated code
Atmospheric model

\[ F_{\text{net}} = \sigma(T_{\text{eff}}^4 - T_{eq}^4) \]

\[ T(z) \text{ profile with } T_s=1400 \text{ K, } P_{\text{CO}_2} = 100 \text{ bars and } P_{\text{H}_2\text{O}}=300 \text{ bars} \]

(Ex: Earth inventory)
Coupled Model

- Volatile exchange between Magma Ocean and atmosphere:
  Atmosphere in equilibrium with magma ocean liquid

- Heat conservation

- Initial conditions:
  - $T_p=4000^\circ K$
  - no atmosphere
  - 0.014 to 0.14 wt% H2O or CO2 (100<P<1000 bars)
Magma Ocean History

\[ \delta = \frac{k(T_p - T_s)}{F_s} \]
Magma Ocean History

Water condensation at the beginning of the mush stage
Influence of atmosphere
Influence of Volatile content

(a) Partial pressure (Bar) vs. Time (Myr)
- Totally molten stage
- Partially molten stage
- "Mush" stage

(b) Partial pressure (Bar) vs. Time (Myr)
- Totally molten stage
- Partially molten stage
- "Mush" stage

End of Magma ocean sensitive to volatile content

Lebrun et al, JGR Planet, in press
Influence of Distance to the Sun
Water Condensation

- Distance from the sun (AU)
- Initial H$_2$O content ($10^{-2}$ Wt%)
- Incident solar flux (Wm$^{-2}$)
- Vapor water condensation time (Myr)

The diagram shows the relationship between initial H$_2$O content, distance from the sun, incident solar flux, and vapor water condensation time. The regions labeled 'Water condensation' and 'No water condensation' indicate areas where water condensation occurs or does not occur, respectively.
Water Condensation

- Distance from the sun (AU)
- Initial H$_2$O content (10$^{-2}$ Wt%)
- Incident solar flux (Wm$^{-2}$)
- Vapor water condensation time (Myr)
- Initial CO$_2$ content (10$^{-2}$ Wt%)
- No water condensation
- Water condensation

Legend:
- Red: Water condensation
- Blue: No water condensation
Water Condensation

![Diagram showing water condensation as a function of initial H₂O content, distance from the sun, incident solar flux, and radius of the planet. The diagrams illustrate regions where water condensation occurs and where it does not.]
Conclusions

- Atmosphere delays the end of magma ocean

- Initial CO2 content controls the ability to condensate a water ocean for distance to the Sun greater than 0.66 AU.

- Time to condensate water ocean on
  - Earth ~ 1 Myr
  - Mars ~ 0.1 Myr
  - Venus ~10 Myr

- $t_{\text{end}} < \text{accretion time}$
  $\Rightarrow$ water ocean can escape

Perspectives

- Magma ocean model: rotation, petrology,…
- Atmospheric model, initial volatile content
- Multiple impact scenario