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**Outline**

- Introduction / constraints
- Heat and volatile transfer during MO Phase
- Examples, results and applications to exo-planets

**Figure 1** Conceptual view of Earth evolution, identifying the three crucial elements (the initial condition, the evolution path, and the present state) and the sciences that contribute to their understanding. The axes are unimportant, since the diagram is merely a 2-D slice of a multidimensional phase space. They might represent temperature or composition, for example.

*Stevenson, 2014*
Introduction / constraints: primary atmosphere

Gaillard et al., 2021
Dissipation of gas in the protoplanetary gas confirmed around 10 My by datation using short lived Pd-Ag system on Iron meteorites (Hunt et al., 2022)

Constraints on the time of formation of Earth
Hf-W + U pb: ~30 – 100 My and Mars: 1 – 10 My measured on martian meteorites

*Figure 1* The timing of events in the early Solar System (Data and models: Dauphas and Pourmand, 2011; Hutcheon et al., 2009; Movshovitz et al., 2010; Qin et al., 2008; Sung et al., 2009; Touboul et al., 2007).
Introduction / constraints: different types of meteorites

Solidified magma

From core-mantle boundary

Fragments of planetary cores

*Planétologie, Sotin et al., Dunod*
Introduction / constraints: accretion models

These ages compatible with accretion models

Fig. 3 Figure from Walsh et al. (2011) showing a simulation of the Grand Tack scenario. The top three panels

O Brien, 2018
**Introduction / constraints:**

Super Earth less than $20 \, M_\oplus$

Diversity in H content

- 10% hydrogen
- 1% hydrogen
- Rocky bodies

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*Massol, 2016 based on Lopez and Fortney, 2014*
Introduction / constraints:
Introduction / constraints: Magma oceans

Cause of magma ocean

- Blanketting by a dense primary atmosphere
- Impacts
- Radiogenic elements (Al26)

Image Credit: NASA/JPL-Caltech

Introduction / constraints: Magma oceans

Figure 5.1 Bold line shows a typical growth curve from an N-body simulation [run2a of Raymond et al., 2014] where arrows indicate giant impacts. The thin line assumes growth at an exponentially decaying rate (equation 5.4) with timescale \( t \) of 10 Myr and a later final Moon-forming impact. Exponential growth models with longer e-folding timescales have been used to reproduce the HF-W and U-Pb isotope systematics of the Earth [Halliday, 2004; Rudge et al., 2010] under the assumption of incomplete re-equilibration during impacts (Section 5.2.4.1). \( M_1 \) is one Earth mass.

Chao, 2021

Nimmo & Kleine 2015
Introduction / constraints: Magma oceans

Fig. 3. Late-time thermal stage following the impact shown in Fig. 2. (a) Low impact Froude number, $Fr \simeq 6$, $U \simeq 1.3 \text{ m s}^{-1}$. (b) High impact Froude number, $Fr \simeq 100$, $U \simeq 5.4 \text{ m s}^{-1}$. In both experiments $P \simeq 0.02$ and the impactor radius $R \simeq 3 \text{ cm}$. The experiments in (a) and (b) correspond to supplementary movies S1 and S2, respectively.

Nimmo & Kleine 2015

Landeau et al., 2021
Certaines petites planètes sans atmospheres primitives vont pouvoir former une atmosphere secondaire Par dégazage.

Gaillard et al. 2022

Hirschmann, 2022

IW: $f_{O_2}$
Introduction / constraints: Volatiles

Altewegg et al., 2015
CometWatch - NavCam images, ESA 7/7/2015

Tchourioumov gerasymenko
Introduction / constraints: water

~$18.3^{+81}_{-3} \text{EO}$

**Fig. 1** Sketch illustrating the “water” species present in the various phases of the Earth’s mantle and crust. The size of the pie slices represents the approximate volume percentage of the phases. The main reservoir of water in the mantle is nominally anhydrous minerals where hydrogen (H) enters their lattice in defects, and bonds to structural oxygen (*blue field*) (Bell and Rossman 1992b). *Olivine, pyroxene and garnet can incorporate water as $H_2$ under reduced conditions (Yang et al. 2016). **K-feldspar can sometimes include water as $H_2O$ and $NH_4$ (Johnson and Rossman 2004)*

*Peslier et al., 2017*
Outline

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Heat and volatile transfer during Magma Ocean Phase

(a) Heat flux and convection in the magma ocean.

(b) Temperature profile with depth.

Legend:
- Net Solar flux
- Escape processes

Mathematical expression:

\[
SC = \int_{R_b}^{R_p} \rho C_p \frac{dT_p}{dt} r^2 dr = R_p^2 Q_S + R_B^2 Q_B + H_{int} + H_{sol}.
\]

Massol et al., 2016
Coupled model

ATMOSPHERE
- 1D Plan parallel

MANTLE
- Parameterized convection, $F_{\text{conv}} \propto Ra^{1/3}$
- Bottom up solidification

Salvador et al., 2017
\[ u \equiv 0 \quad \bar{\rho} = \rho_0 (1 + \beta z) \]

Statically stable

\[ \bar{\rho} \]

\[ \beta < 0 \]

\[ z \]

\[ \rho^+ \]

Statically unstable

\[ \bar{\rho} \]

\[ \beta > 0 \]

Important physical parameters:

\[ g, \nu, \kappa, \beta \]

Dimensions:

\[ LT^{-2}, L^2 T^{-1}, L^2 T^{-1}, L^{-1} \]
Spherical particle of radius $h$
Displaced upward of $h$ in a time $\tau$
- Characteristic velocity $U$?

- Potential energy gained $E$?

- How much time for the particle to lose buoyancy?

- What is the energy $D$ dissipated by viscous forces?
Characteristic velocity: \( U \propto \frac{h}{\tau} \)

Potential energy gained: \( E \propto (\Delta \rho h^3) gh \)
\( \propto \rho_0 \beta hh^3 gh \)
\( \propto \rho_0 \beta gh^5 \)

The particle lose buoyancy in a time: \( \tau \propto \frac{h^2}{\kappa} \)

Energy \( D \) dissipated by viscous forces: \( D \propto \mu \frac{U}{h} h^2 h \propto \mu \frac{h^3}{\tau} \propto \mu kh \)

Instability if \( E > D \) \( \rho_0 \beta gh^5 > \mu kh \) i.e.: \( Ra = \frac{\beta gh^4}{\kappa \nu} > 1 \)
Heat and volatile transfer during Magma Ocean Phase: Ra

Convective patterns as a function of Rayleigh number:

\[ Ra = \frac{\alpha g \Delta T h^3}{\kappa \nu} \]

with \( \beta = \frac{\alpha \Delta T}{h} \)

up to \( Ra = 30 \) for entirely liquid MO

*Figure 4* Convection patterns of a fluid heated from below at Rayleigh number \( 10^5, 10^6, 10^7, 10^8 \). The temperature color bars range from 0 (top boundary) to 1 (bottom boundary). The Boussinesq approximation was used (numerical simulations by F. Dubuffet). The increase in Rayleigh number corresponds to a decrease of the boundary layer thicknesses and the width of plumes. Only in the case of the lowest Rayleigh number (top left) is the convection stationary with cells of aspect ratio \( \sim \sqrt{2} \) as predicted by marginal stability. For higher Rayleigh number, the patterns are highly time dependent.

Ricard, 2007
Viscosity

After Takei and Holtzmann 2009

Interpolation between $\eta_s$ (Karato et Wu, 1993) et $\eta_l$ (Karki et Stixrude, 2010)

Salvador et al., 2017
Heat and volatile transfer during Magma Ocean Phase

Andrault et al., 2016
Exsolution

More references in Iacono et al., 2012
Mass conservation of volatiles

\[ M_{vol}^{\text{solid}} + M_{vol}^{\text{liquid}} + M_{vol}^{\text{atm}} = X_{vol,t=0}M_{t=0}^{\text{MO}} \]

\[ M_{vol}^{\text{atm}} = \frac{4\pi R_p^2}{g} \left( \frac{\mu_{vol}}{\bar{\mu}} \right) P_{vol}(X_{vol}^{\text{liquid}}) \]
Definition: End of Rapid Cooling Stage

- Limit between two evolution stages:
  - Controlled by $F_{conv}$, vigorous mantle convection, strong cooling, degassing of the atmosphere
  - Controlled by $F_\odot$, quasi steady-state: $T_{surf}$ and $P_{atm}$, other geodynamic regime

- ERCS taken at time when $F_{conv} = \frac{1}{10} F_\odot$
- Introduction / constraints
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Examples, results and applications

Time evolution

\[ \text{CO}_2: 600 \text{ ppm; H}_2\text{O}: 0.4 \text{ EO; D}=1 \text{ AU; } \alpha=0.2 \]
Examples, results and applications

Degassing

\[ \text{CO}_2: 600 \text{ ppm; } \text{H}_2\text{O: 0.4 EO; } \text{D=1 AU} \quad \alpha=0.2 \]
Examples, results and applications

Distance to the sun

0.77

1.3

End of Rapid Cooling Stage

ERCS: \( F_{\text{conv}} \leq 0.1 \times F_{\odot} \)

Volatiles

\( \text{H}_2\text{O} = 0.6 \text{ MEO, CO}_2 = 500 \text{ ppm} \)
Examples, results and applications

CO₂ content

CO₂: 400 ppm; H₂O: 0.6 EO; D=1 AU; α=0.2

CO₂: 1200 ppm; H₂O: 0.6 EO; D=1 AU; α=0.2
$\text{H}_2\text{O} = 0.6 \text{ MEO, } \alpha = 0.2$

- partial melt
- no condensation
- condensation post ERCS
- condensation at ERCS

Examples, results and applications

- "Type II"
- Hamano, 2013

Absorbed solar flux $F_{\odot} [W.m^{-2}]$

- No water condensation
- "Type I"
- "Type I"

Water condensation
For different initial water content

Absorbed solar flux $F_\odot [W.m^{-2}]$

$D_C \rightarrow 1.243M_{EO}$

$0.621M_{EO}$

$0.371M_{EO}$

$0.186M_{EO}$

$0.062M_{EO}$

$0.031M_{EO}$

Initial CO$_2$ content [$10^{-2}$ wt%]

Solar distance [AU]
Scaling

volatiles

\[ x^* = \frac{x[0]_{CO_2}}{x[0]_{CO_2} + x[0]_{H_2O}} \]

Distance to the star

\[ D_C = \sqrt{\frac{F_0(1-\alpha)}{F_{IR}}} \]

\( F_0 \) being the solar constant for the young sun and \( F_{IR} \) the Nakajima limit (280 W m\(^{-2}\)
In Marcq et al. model used here)

\[ D^* = \frac{D}{D_C} = 0.814 \]
Examples, results and applications

Venus

For a 0.4 albedo it requires 0.13 Earth Ocean \( (x^* \approx 0.65) \)
Examples, results and applications

Meier, 21 (LHS 3844b)
Dorn and Lichtenberg, 21 (Trappist 1f)
Cadieux, 22 (TOI1452b)

Massol et al. in prep.
Conclusions perspectives

Perspectives:
- Post MO Heat and volatile transfer
- Surface conditions and fracturation

Application to exoplanets: remarks, questions?