Geophysical evolution during rocky planet formation

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Exoplaneten und **Habitabilität**

Core dynamo magnetic field lines
Core convection
Plate tectonics
Surface ocean
Dry surface
No dynamo magnetic field
No core convection
Stagnant lid
Rocky planets as evolving worlds

Gaillard & Scaillet 14

Driscoll+19
Overview

- Waterworlds vs. $^{26}$Al
- Solar system chronology: Earth-forming reservoirs
- Earth-like surfaces & atmospheres on rocky exoplanets
Overview

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Exoplanet diversity

Modified from Kaltenegger 17

H₂/He

Fe

H₂/He

Ice mantle

Liquid water

Water world

Earth-like world

Liquid water (shallow)

$F/F_{\text{Earth}}$ vs. $T$ [K]

Planet radius [$R_{\text{Earth}}$]

Planet mass [$M_{\text{Earth}}$]

$H₂/He$

$Fe$

$H₂$

$Sotin+07; Meyer+08; Vadim Sadovski; NASA/JPL-Caltech$

$f_w > 1 \text{ wt\%}$

$f_w \approx 0.1 \text{ wt\%}$

100% H₂O

50% H₂O

25% H₂O

MgSiO₃ (rock)

25% Fe

50% Fe

100% Fe
Waterworlds

Water world

- $f_w > 1$ wt%
- Ice mantle
- Liquid water

Earth-like world

- $f_w \approx 0.1$ wt%
- Liquid water (shallow)
Radiogenic heating in early Solar System

![Radiogenic heating diagram](image)

- Disk lifetimes
- Radiogenic heating, log$_{10}$ [W/kg]
- $^{26}\text{Al}$ ($t_{1/2} = 0.716$ Ma)
- $^{60}\text{Fe}$ ($t_{1/2} = 2.62$ Ma)
- $^{40}\text{K}$ ($t_{1/2} = 1400$ Ma)
- $^{235}\text{U}$ ($t_{1/2} = 704$ Ma)
- Total heating

Time after Solar system formation [Myr]
Planet accretion altered by $^{26}\text{Al}$

Prospective radiogenic heating in exo-planetesimals, $H_r$ [W/kg] ~ $10^2 - 10^8 \times$ Earth’s present-day interior radiogenic heating
Water loss from planetesimals

Stability of hydrated silicates

- **hydrated silicates**
- **dry silicates**

**Approx pressure at center of Vesta-sized undifferentiated planetesimal**

**chondritic melts**

**T = 0 °C: Water ice melts**

**silicate melting**

**Decay of planetesimal water abundance**

**Retained water, log \( f_{\text{H}_2\text{O}}(t)/f_{\text{H}_2\text{O,init}} \)**

**Time after planetesimal formation \( t \) [Myr]**

Fu & Elkins-Tanton (2014)
\( ^{26}\text{Al} \) shapes exoplanet structure

**Solar \(^{26}\text{Al} \) versus no \(^{26}\text{Al} \) heating**

- Protoplanets w/ \( f_{\text{H}_2\text{O}} > 0 \)
- \( f_{\text{H}_2\text{O}} = 0 \)
- \( f_{\text{H}_2\text{O}} > 0 \)

**Intra-system size correlation** (Weiss+ 18, Milholland+ 18)

- Median
- Interquartile range

**Final bulk planet water mass fraction [wt\%]**

- \( 0.1 \times ^{26}\text{Al}_\odot \)
- \( 0.3 \times ^{26}\text{Al}_\odot \)
- \( 1.0 \times ^{26}\text{Al}_\odot \)
- \( 10 \times ^{26}\text{Al}_\odot \)
$^{26}\text{Al}$ shapes distribution systematics

Intra-system size correlation (Weiss+ 18, Millholland+ 18)

Insensitive to orbital location

TRAPPIST-1 (Grimm+ 18, Dorn+ 18)

bulk planet water mass fraction [wt%]
$^{26}$Al shapes distribution systematics

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Near-future M star statistics? (Ballard 19)
$^{26}$Al key control on rocky planet composition

- Fraction of planetary systems enriched with $^{26}$Al
  - Volatile loss & differentiation in planetesimals
- Systemic dichotomy:
  - Enriched: water-poor (proto-)planets
  - Not-enriched: ocean worlds
- Statistically traceable w/ near-future data?
  - Discernible by *transit radius* alone
  - Increasing statistics on M star systems
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Planet formation at home and abroad*

*Raymond+ 14

Live $^{26}$Al ($t_{1/2} \sim 0.7$ Ma)

- Protoplanet accretion
- Iron meteorite formation
- Chondrite accretion
- Mars accretion

Modified from Nittler & Ciesla 16
Distinct reservoirs?
Inferred growth of Jupiter
Hard vs. model-dependent constraints

-Kruijer+17

[Graph showing the time of core formation (My) against time of accretion (My), with different groups labeled: 'Carbonaceous' groups (IIC, IID, IIF) and 'Non-carbonaceous' groups (IC, IIAB).]

[Diagram illustrating snapshots of disk evolution during Jupiter's growth, with stages labeled: Stage 1, Stage 2, Stage 3, Stage 4, and showing time of parent body accretion and time after CAI formation (My).]
Alternative: structured disk
Alternative: structured disk
Structured disk

- Traffic jam + cold finger
- Cold finger
- Snow line

Time after CAIs, $t$ [Myr]

Log $\dot{\Sigma}_{\text{pits}}$ [g cm$^{-2}$s$^{-1}$]

Orbital distance, $r$ [au]
Structured accretion generates distinct signatures
Structured accretion generates distinct signatures

- Reservoir separation may be traced back to disk turbulence
  - Not dependent on the presence of a cold Jupiter planet, but *causing* it
- Relationship between super-Earth occurrence and disk structure?
- Rocky planets *formed* before giant planets
- Water accretion sequence to Earth: water-rich - dry - water-rich
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Magma ocean – atmosphere

Legend: Red arrow = Net Solar flux, Blue arrow = Escape processes
Magma ocean – atmosphere – surface

Water-rich planet

Dry planet

Legend: Net Solar flux Escape processes

Orbital distance [AU]

Final water inventory [Earth Oceans]

1 M_{Earth}, G star

Initial

Initial inventory (M_{EO})
Magma ocean – atmosphere

Legend: Net Solar flux, Escape processes

Solomatov 15; Massol+16

Dasgupta & Hirschmann 10,12; Hirschmann+ 10,12,16,18
Magma ocean – atmosphere – surface

Legend: 
- Net Solar flux
- Escape processes
Exoplanet diversity

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Rocky planets from formation to early evolution

- Formation phase sensitive to system’s characteristics
- Early Solar System chronology proxy for what we consider ‘Earth-like’
- Rocky exoplanets subject to order of magnitude variations in volatile content and mixing ratios
  - Different surface expressions and geochemistry (and thus habitability)