Redox hysteresis of super-Earth exoplanets from magma ocean circulation

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exoplanet-talks.org/talk/359
Composition of secondary atmospheres

Secular geodynamic evolution

- Late accretion
- Solid state convection
- Volcanic degassing
- Secondary atmosphere

Magma ocean crystallization

- Indoor core nucleation
- Overturn
- Interior-atmosphere equilibration

Exsolution dynamo

- Mantle oxidation
- Proto-core merging

Core-mantle equilibration

- Proto-mantle
- Secular growth

Scaled planet radius

Giant impact phase

- Impact melting
- Nebular ingassing
- Global magma ocean
- Metal rainout
- Radiogenic degassing
- Metal percolation

Planetary stage

- Primordial atmosphere
- Nebular atmosphere
- Proto-core merging
- Core-mantle equilibration

~10^6 yr
- Solid state convection
- Proto-mantle
- Scaled planet radius

~10^6–10^8 yr
- Solid state convection
- Proto-mantle
- Scaled planet radius

~10^6–10^9 yr
- Proto-core
- SECULAR growth
- Planetesimal stage

~10^7 yr
- Proto-core merging
- Core-mantle equilibration
- Interior atmosphere equilibration

~10^8 yr
- Proto-core merging
- Core-mantle equilibration
- Interior atmosphere equilibration

~10^8–10^9 yr
- Proto-core merging
- Core-mantle equilibration
- Interior atmosphere equilibration

Lichtenberg, Schaefer, Nakajima, Fischer 2022, Protostars & Planets VII
Composition of secondary atmospheres

Discovery path

H/He > solids

H/He accretion limit

Runaway H/He accretion

H/He loss limit

Runaway greenhouse limit

Impact escape limit

Hydrodynamic escape limit

Surface melting

Tenuous gas envelope

Instellation

Lichtenberg, Schaefer, Nakajima, Fischer 2022, Protostars & Planets VII
Composition of sub-Neptunes & super-Earths
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Swain+ 21

Mugnai+ 21
Libby-Roberts+ 21

GJ 1132b

K2-18b
Redox-controlled climates

\[ P_{\text{surf}} = 1 \text{ bar} \]
\[ T_{\text{surf}} = 1400 \text{ K} \]

Lichtenberg, Schaefer, Nakajima, Fischer, +22, Protostars & Planets VII

Volatile mixing ratio (\( \log_{10} X_i \))

Redox state relative to iron-wüstite buffer (\( \Delta \text{IW} \))

\[ \text{IW: } 2(1-x) \text{Fe} + \text{O}_2 = 2 \text{Fe}_{1-x}\text{O} \]
Atmosphere composition related to planetary size

Reduced atmospheres: $\text{H}_2, \text{CO}, \text{CH}_4$

Oxidised atmospheres: $\text{H}_2\text{O}, \text{CO}_2, \text{SO}_2$

~Moon  ~Mars  ~Earth

Deng+ 20, Grewal+ 20, Gaillard+ 21
Redox alteration requires reservoir mixing

Iron disproportionation

\[ 3\text{Fe}^{2+} \rightarrow 2\text{Fe}^{3+} + \text{Fe}^0 \]

Frost+ 04, Wade & Wood 05, Frost & McCammon 08, Carlson+ 12

Endogenous water production

\[ \text{FeO} + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{Fe}^0 \]

Ikoma & Genda 06, Ikoma+ 18, Olson & Sharp 18, Kite & Schaefer 21

- Mixing: atmosphere-mantle
- Mixing: mantle-core

Require:
Turbulent convection in sub-Neptunes

\[ Ra = \frac{\alpha \rho g \Delta T D^3}{\kappa \eta} \]

- Melt density
- Thermal expansivity
- Gravity acceleration
- Thermal gradient
- Thermal diffusivity
- Melt viscosity
- Magma ocean depth
Particle settling in turbulent convection

Inertial particles

Atmosphere

Mantle

Metal core

Non-dimensional temperature

\( \frac{T - T_0}{\Delta T} \)

Pr = 50  \quad Ra = 10^{12}
Turbulent convection in sub-Neptunes

Expected iron droplet sizes

\[ d_{\text{droplet}} \approx \frac{\sigma \cdot \text{We}}{\Delta \rho \cdot v_{\text{magma}}^2} \]

Size threshold for suspension

\[ d_{\text{crit}} \approx \frac{\rho_{\text{magma}}(v_{\text{magma}}/60)^2}{0.1 \Delta \rho \cdot g} \]

Rubie+ 03, Solomatov 15
Rainout quenching in sub-Neptune interiors

$d_{\text{droplet}}$ vs. $d_{\text{crit}}$

Planetary heat flow $F_{\text{MO}}$ (W m$^{-2}$)

- $10^6$
- $10^5$
- $10^4$

Primordial atmosphere

Iron droplet diameter [cm]

Expected sizes

Sizes entrained

Terrestrial planets
Super-Earths

Magma circulation
Gravity

Planetary heat flow

Lichtenberg, ApJL 2021
Rainout quenching in sub-Neptune interiors

Rainout quenched

Planetary heat flow

Magma circulation

Gravity

Lichtenberg, ApJL 2021
Magma circulation affects redox balance

(A) Mantle self-oxidation

\[
\begin{align*}
    \text{Fe}^{2+} & \rightarrow \text{Fe}^0 + \text{Fe}^{3+} \\
    \text{FeO} + \text{H}_2 & \rightarrow \text{Fe}^0 + \text{H}_2\text{O}
\end{align*}
\]

(B) Redox hysteresis

\[
\begin{align*}
    \text{Fe}^{2+} & \Leftrightarrow \text{Fe}^0 + \text{Fe}^{3+} \\
    \text{FeO} + \text{H}_2 & \Leftrightarrow \text{Fe}^0 + \text{H}_2\text{O}
\end{align*}
\]
Magma circulation affects \textbf{composition}

(A) Mantle self-oxidation

$$\text{Fe}^{2+} \rightarrow \text{Fe}^0 + \text{Fe}^{3+}$$

$$\text{FeO} + \text{H}_2 \rightarrow \text{Fe}^0 + \text{H}_2\text{O}$$

(B) Redox hysteresis

$$\text{FeO} + \text{H}_2 \Rightarrow \text{Fe}^0 + \text{Fe}^{3+} + \text{H}_2\text{O}$$

Lichtenberg, ApJL 2021
Prebiotic chemistry on reduced super-Earths?

(A) Mantle self-oxidation

(B) Redox hysteresis

\[ \text{Reduced atmosphere} \rightarrow \text{Oxidized atmosphere} \]

- FeO + H₂ \rightleftharpoons Fe⁰ + H₂O

- Fe²⁺ \rightleftharpoons Fe⁰ + Fe³⁺

Cyanoacetylene

Range of values with different HCN & CH₄ composition

With Cloud
Redox hysteresis of super-Earth exoplanets from magma ocean circulation

Internal magma circulation of sub-Neptune exoplanets may substantially affect compositional properties and speciation of secondary atmospheres:

- Turbulent flow can suspend iron and protract core-mantle differentiation
- Rainout quenching sustains mantle composition and limits mantle redox evolution
- May lead to observable differences in exoplanet properties:
  - \textit{Rainout quenched regime}: reduced atmospheres + interiors, cool faster
  - \textit{Redox altered regime}: oxidised atmospheres, prolonged magma ocean phase