ESA/Hubble, M. Kornmesser

Redox hysteresis of super-Earth exoplanets from magma ocean circulation

The Astrophysical Journal Letters 914, L4 (2021)

exoplanet-talks.org/talk/359

Tim Lichtenberg

Background: Vojtěch Patočka

timlichtenberg.net | @tim_lichtenberg

NASA, ESA, and R. Hurt (IPAC/Caltech)

Composition of secondary atmospheres

Lichtenberg, Schaefer, Nakajima, Fischer 2022, *Protostars & Planets VII*

Composition of secondary atmospheres

Lichtenberg, Schaefer, Nakajima, Fischer 2022, *Protostars & Planets VII*

Composition of sub-Neptunes & super-Earths

Composition of sub-Neptunes & super-Earths

Swain+ 21

Mugnai+ 21
Libby-Roberts+ 21

GJ 1132b

NASA, ESA, and R. Hurt (IPAC/Caltech)

K2-18b

ESA/Hubble, M. Kornmesser

Composition of sub-Neptunes & super-Earths

Swain+ 21

Mugnai+ 21
Libby-Roberts+ 21

Benneke+ 19

GJ 1132b

K2-18b

NASA, ESA, and R. Hurt (IPAC/Caltech)

Redox-controlled climates

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

Redox state relative to iron-wüstite buffer (Δ IW)

IW: $2(1\text{-}x)\ Fe + O_2 = 2\ Fe_{1-x}O$

Atmosphere composition related to planetary size

Deng+ 20, Grewal+ 20, Gaillard+ 21

Redox alteration requires reservoir mixing

Iron disproportionation

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

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

Endogenous water production

$$FeO + H_2 \rightarrow H_2O + Fe^{0}$$

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

Require:

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

?

Turbulent convection in sub-Neptunes

Melt density

Thermal gradient

Thermal expansivity

Gravity acceleration

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

Magma ocean depth

Thermal diffusivity

Melt viscosity

Particle settling in turbulent convection

Patočka+ 20, Phys. Rev. Fluids

Turbulent convection in sub-Neptunes

Expected iron droplet sizes

Surface energy

Weber number

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

Iron-magma density difference

Fluid velocity

Size threshold for suspension

Magma density

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

Rubie+ 03, Solomatov 15

Rainout quenching in sub-Neptune interiors

d_{droplet} vs. d_{crit}

Lichtenberg, *ApJL 2021*

Rainout quenching in sub-Neptune interiors

d_{droplet} vs. d_{crit}

Lichtenberg, *ApJL 2021*

Magma circulation affects *redox balance*

Lichtenberg, *ApJL 2021*

Magma circulation affects *composition*

H_2O
CO_2
SO_2

Oxidised surfaces

Prolongs magma ocean phase

H_2
CO
CH_4

Reduced surfaces

Enhances chances for detection

Lichtenberg, *ApJL 2021*

Prebiotic chemistry on reduced super-Earths?

Rimmer+ 21, *ApJL*

ESA/Hubble, M. Kornmesser

Redox hysteresis of super-Earth exoplanets from magma ocean circulation

Lichtenberg 2021, *ApJL* 914, L4

exoplanet-talks.org/talk/359

Internal magma circulation of sub-Neptune exoplanets may substantial 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:
  - ✦ *Rainout quenched regime*: reduced atmospheres + interiors, cool faster
  - ✦ *Redox altered regime*: oxidised atmospheres, prolonged magma ocean phase

Background: Vojtěch Patočka

NASA, ESA, and R. Hurt (IPAC/Caltech)