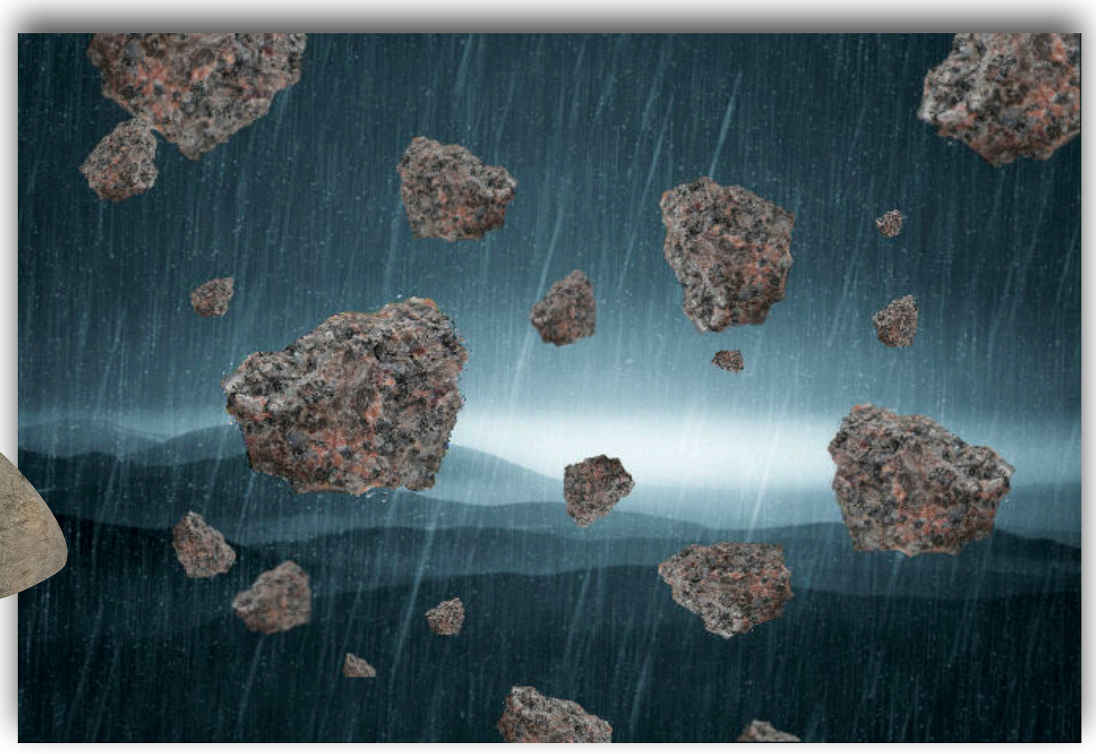
Rain of rocks in sub-Neptunes formed by pebble accretion



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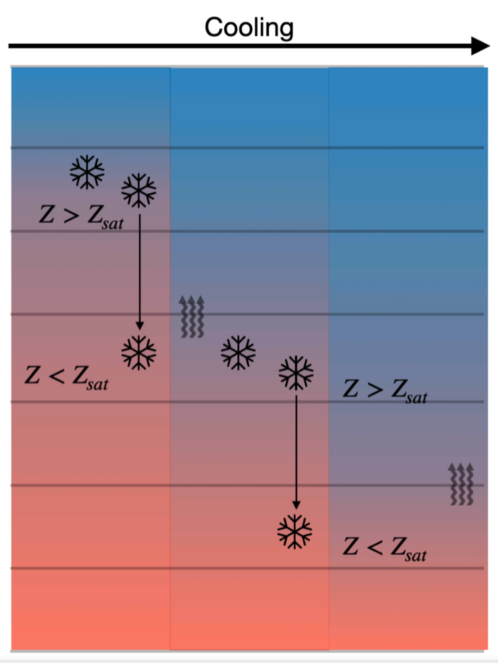
WHAT: Recent modelling of planet formation has highlighted that sub-Neptune planets formed by pebble accretion are characterized by large quantities of silicate vapor in their gas (hydrogen-helium) envelope. Upon cooling this vapor is expected to condense and rain-out into deeper layers. In this work we aim to examine the rainout process and its timescale.

HOW: We calculate thermal evolution of rocky planets formed by pebble accretion. We model the cooling of the polluted envelopes self-consistently with the consequent rainout (condensation and settling) of rocks, and the mass loss by irradiation from the parent star.

RESULTS:

1- Cooling of polluted envelopes

Condensation and settling (rainout) of silicates



Condensation

$\Delta E = \Delta m \times e_{latent}$

Condensation of mass Δm (latent heat)

Settling

$\Delta E = -GM(r_1)\Delta m(\frac{1}{r_0} - \frac{1}{r_1})$

Settling of mass Δm from r_0 to r_1

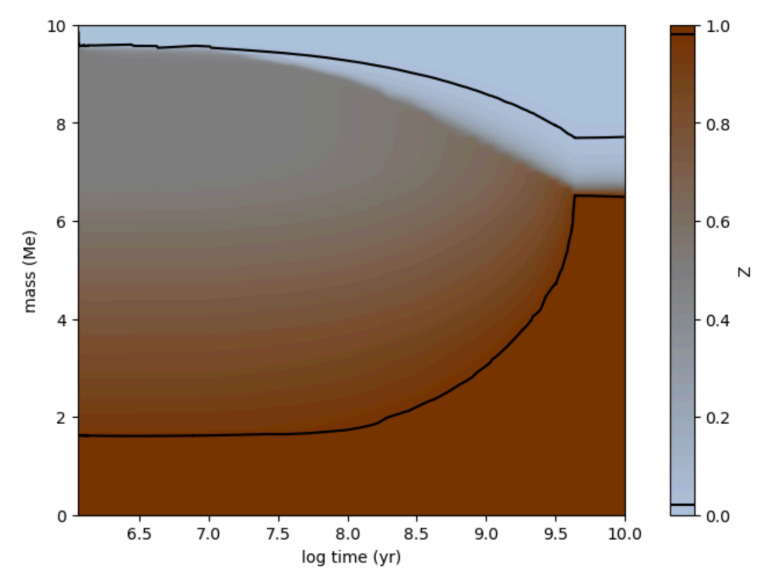
Heat from formation

$\Delta E = \epsilon(m)E_{accterion}$

ε(m) fraction of accretion energy stored in mass m

2 - Interior structure evolution

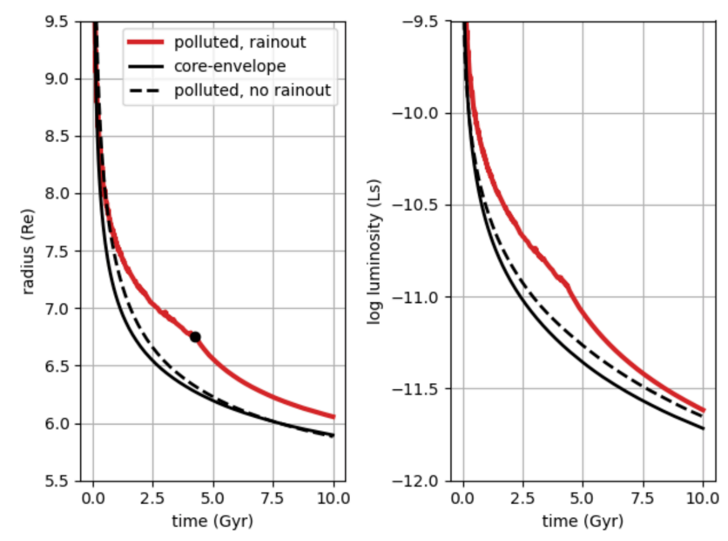
Rain of rocks in sub-Neptune (10M⊕) planet



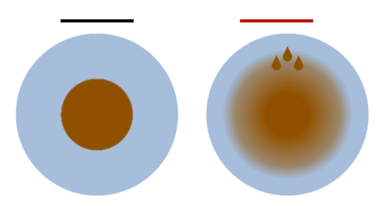
Silicate mass fraction (color) as a function of interior layers (y axis) and time (x axis). Silicate mass fraction ranges between zero (hydrogen-helium only) in blue and pure silicate in brown. The gradual distribution of silicate from planet formation slowly converges into a core-envelope structure within about 4.25 Gyr. The solid lines signify $Z = 0.98$ and $Z = 0.02$ enrichment levels.

3 - Thermal evolution

Energy release by rainout causes radius inflation

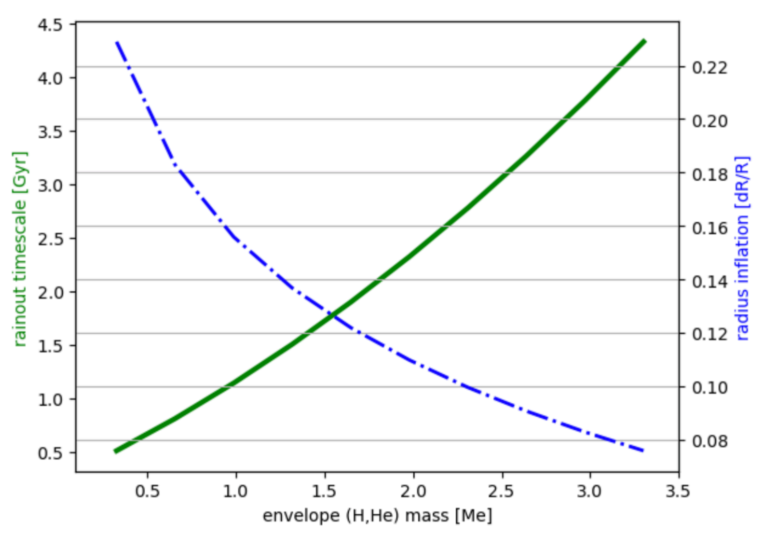


Radius (left) and luminosity (right) evolution of the 10M⊕ planet shown in previous figure (red). The evolution of the same planets without rainout (dashed black) and of planet with same composition in core-envelope structure from formation (solid black) are shown for comparison. The black dot signifies the end of the rainout phase. Radius inflation in that point is 8% in comparison to the core-envelope case.



4 - Dependency on envelope mass

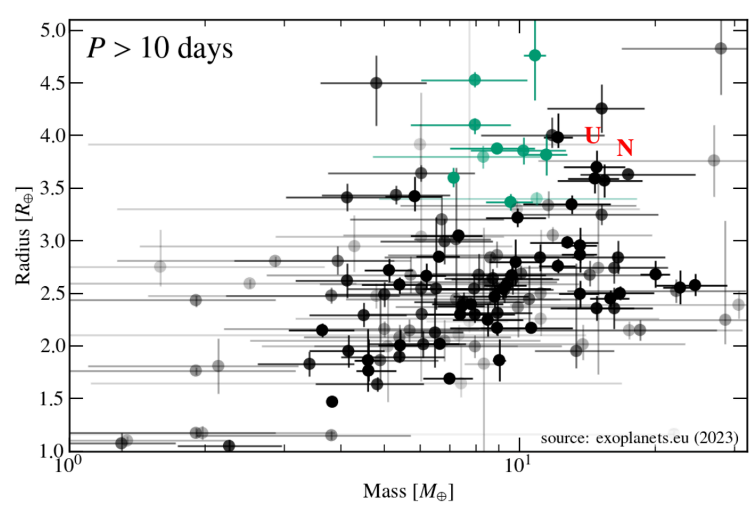
Rainout timescale and radius inflation



Green: time from formation until convergence to a core-envelope structure (rainout timescale) as a function of envelope mass. Trend is shown for sub-Neptune planets that contain 6.7M⊕ of silicates and their gas (H,He) mass ranges from 3.3M⊕ (original model, no mass loss) down to 0.33M⊕.
Blue: radius inflation by rainout in comparison to the core-envelope structure model.
Curves are polynomial fits for the evolution data points.

5 - Exoplanet population

Sub-Neptunes might be inflated by rainout (gray)



Mass-radius relation of observed exoplanets. Planets in the green are potentially inflated by past or ongoing rainout, in comparison to planets that formed with core-envelope structure. The rainout effect on the inferred H,He mass of the exoplanets marked in green appear in the table (right panel). Sub-Neptune planets with radii above 3.4 Earth radii that aren't marked in green lack an age measurement.

Inferred H,He fraction of exoplanets:
Core-envelope vs. formation with polluted envelope

	mass (Me)	radius (Re)	period (days)	age (Gyr)	H,He fraction standard	H,He fraction with rainout
Kepler-36 c	7.13	3.6	16.2	6.9	7.8%	6%
Kepler-11e	7.95	4.1	32	8.5	15%	11%
TOI-1136 d	7.95	4.53	12.5	0.7	13%	6.5%
TOI-1136 f	8.3	3.8	26.3	0.7	9%	4.5%
TOI-1422 b	8.9	3.88	13	5.1	10%	6%
KOI-142 b	9.54	3.37	10.9	2.4	7%	4%
K2-314 d	10.2	3.86	35.7	9	13%	10%
K2-19 c	10.8	4.76	11.9	8	20%	14%
Kepler-79 b	10.9	3.4	13.5	3.4	6.6%	4.5%
Kepler-30 b	11.4	3.8	29.3	2	11%	6%

CONCLUSIONS:

- The cooling of sub-Neptunes formed with polluted envelopes lead to late growth of the rocky core by rainout, where a complete rainout results in a core-envelope structure.
- Timescale for rainout depends on envelope (H,He) mass and age - planets with envelope mass lower than 0.75 M⊕ have core-envelope structure at age of 1 Gyr, while planets with more massive envelopes or younger planets may still be raining-out as we observe them, having interiors with composition gradients and/or polluted envelopes.
- Rainout process causes radius inflation by release of gravitational energy (settling), latent heat (condensation), and formation energy (composition gradient erosion). The radius inflation is a few percent for sub-Neptunes with massive envelopes, and larger but on much shorter timescale in planets with lower mass envelopes.
- Planets that formed with polluted envelopes (> 0.3 M⊕) would look "younger" than planets that formed with core-envelope structure, as a result of the later heat release and radius inflation.
- The larger radii might be inferred, if age is known, as higher H,He content in observed exoplanets (see table).
- Future age measurements by the PLATO space mission are essential to shed light on the rainout process and its importance in the planet formation-evolution sequence.

Vazan & Ormel - submitted to A&A

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