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When does the atmospheric composition represent the planetary bulk composition?

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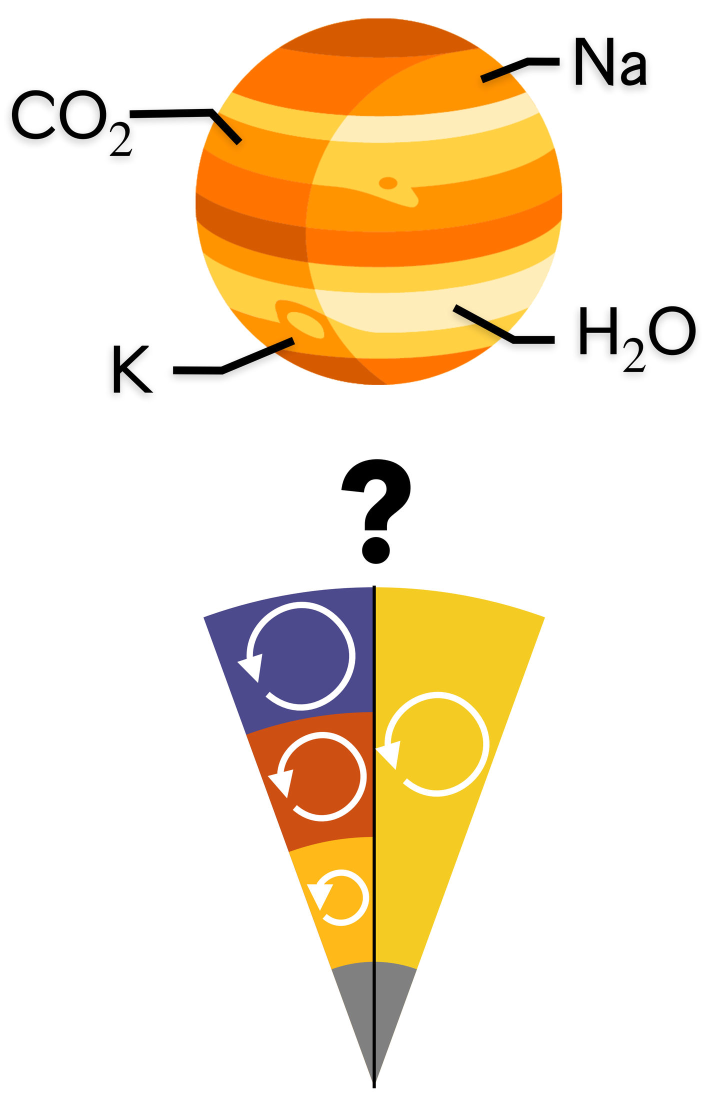
Introduction



Question

Do atmospheric abundance measurements by, e.g., JWST represent the planetary bulk composition?

Idea

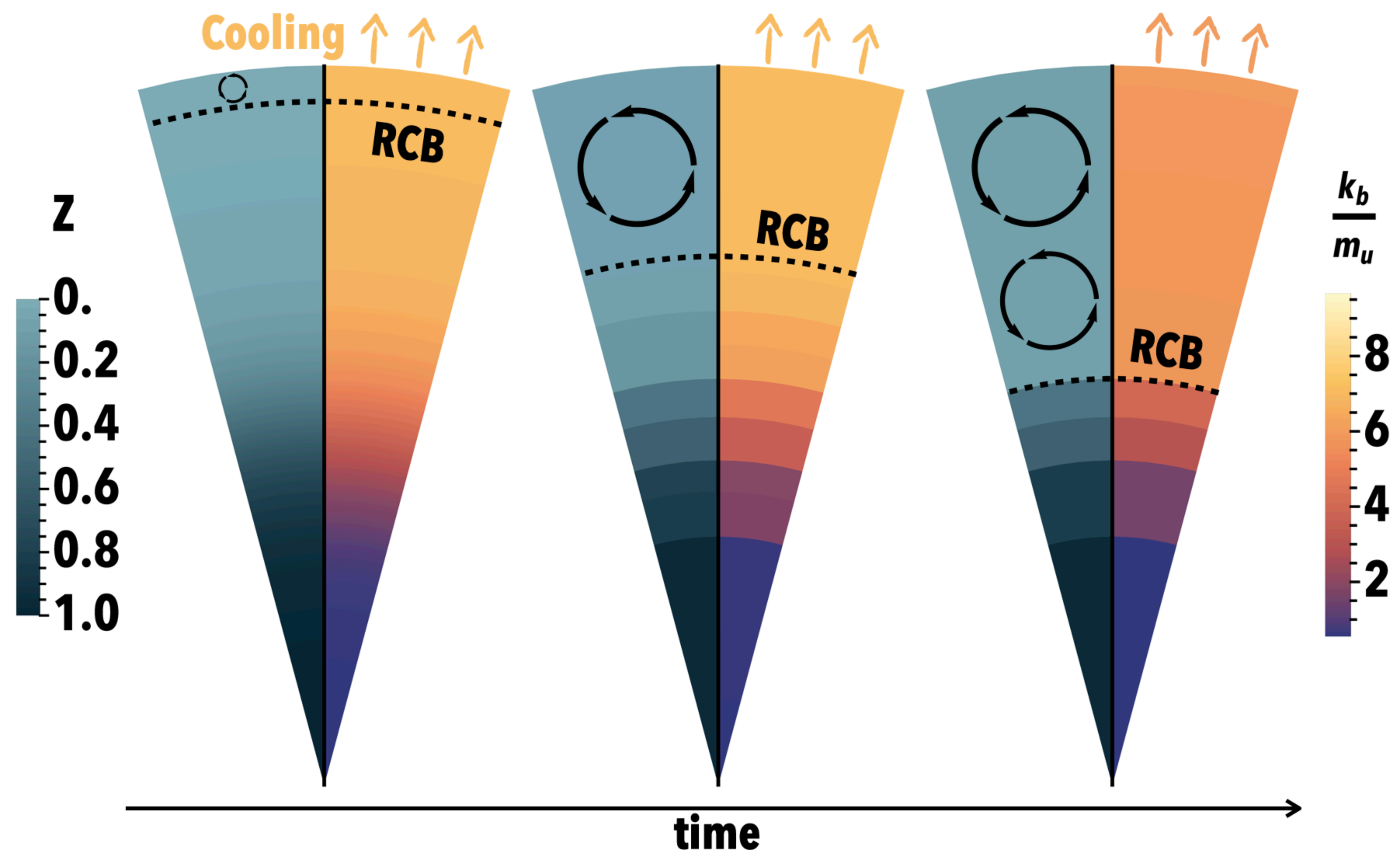
As planets evolve, they undergo mixing due to convection. By understanding when convection begins, we can determine the extent to which the planet will mix.

Goal

Identify the factors that drive mixing in giant planets and determine the conditions under which mixing will or will not occur.

Numerical Methods

We used MESA with state-of-the-art equations of state and improved mixing to solve the full set of evolution equations.



Results

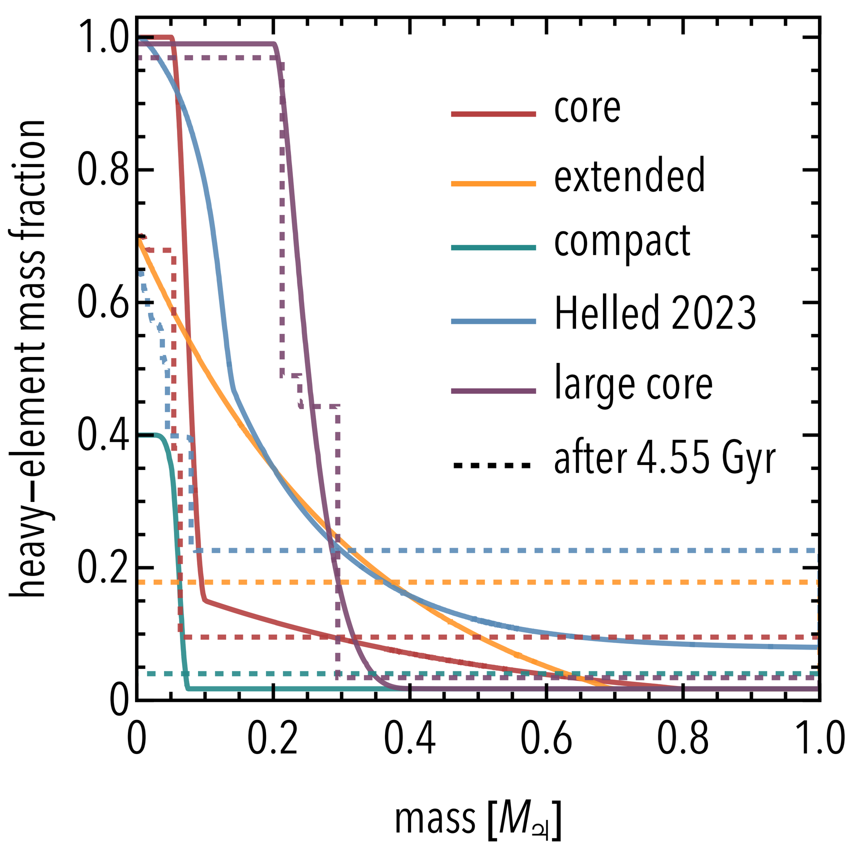


Fig. 1. Heavy-element mass fraction at the beginning and end (4.55 Gyr) of the simulations for $M = 1 M_J$ and $S = 10\ k_B m_u^{-1}$.

High Z is more stable

- We simulated various heavy-element mass profiles.
- Shallow heavy-element mass profiles get eroded.
- Only steep profiles with high heavy-element mass fraction survive over evolutionary timescales.
- The heavy-element mass fraction in the atmosphere can be widely different from the bulk composition.

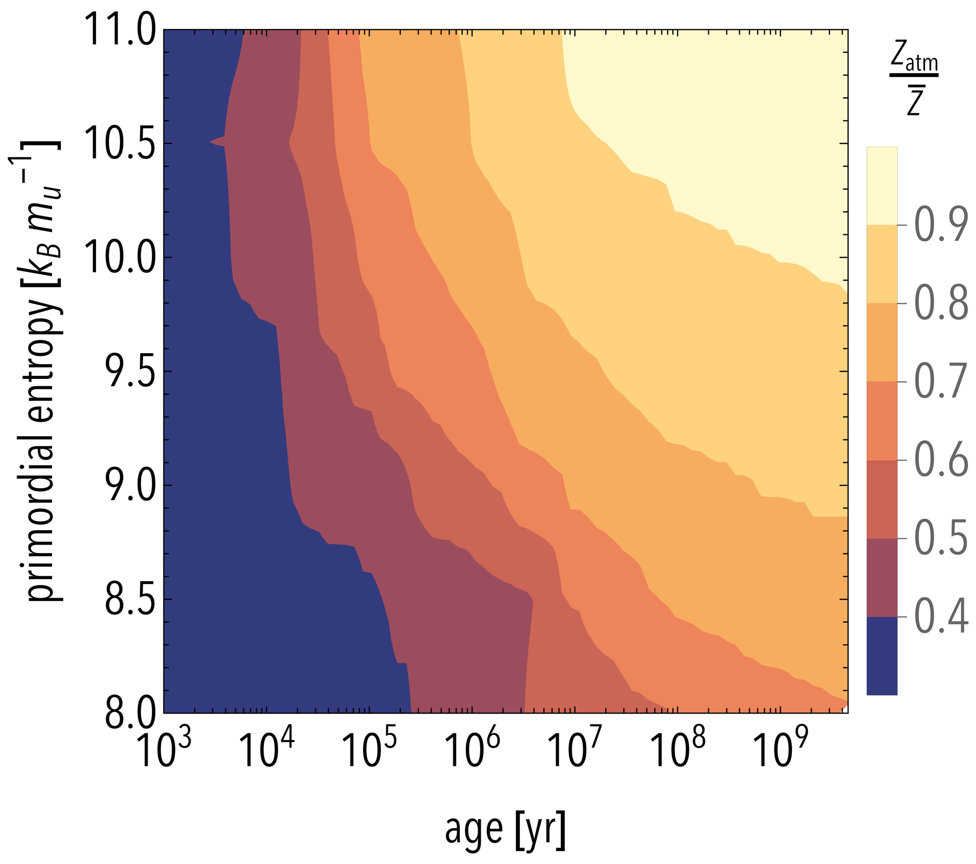


Fig. 2. Time evolution of atmospheric-to-bulk heavy-element mass fraction of model „Helled 2023" for a range of primordial entropies.

More entropy = more mixing

- We simulated primordial entropies between 8 and 11 $k_B m_u^{-1}$.
- Hot (high entropy) planets mix vigorously and rapidly (~10 Myr).
- Cold (low entropy) planets mix comparatively little and can continue mixing over evolutionary timescales.

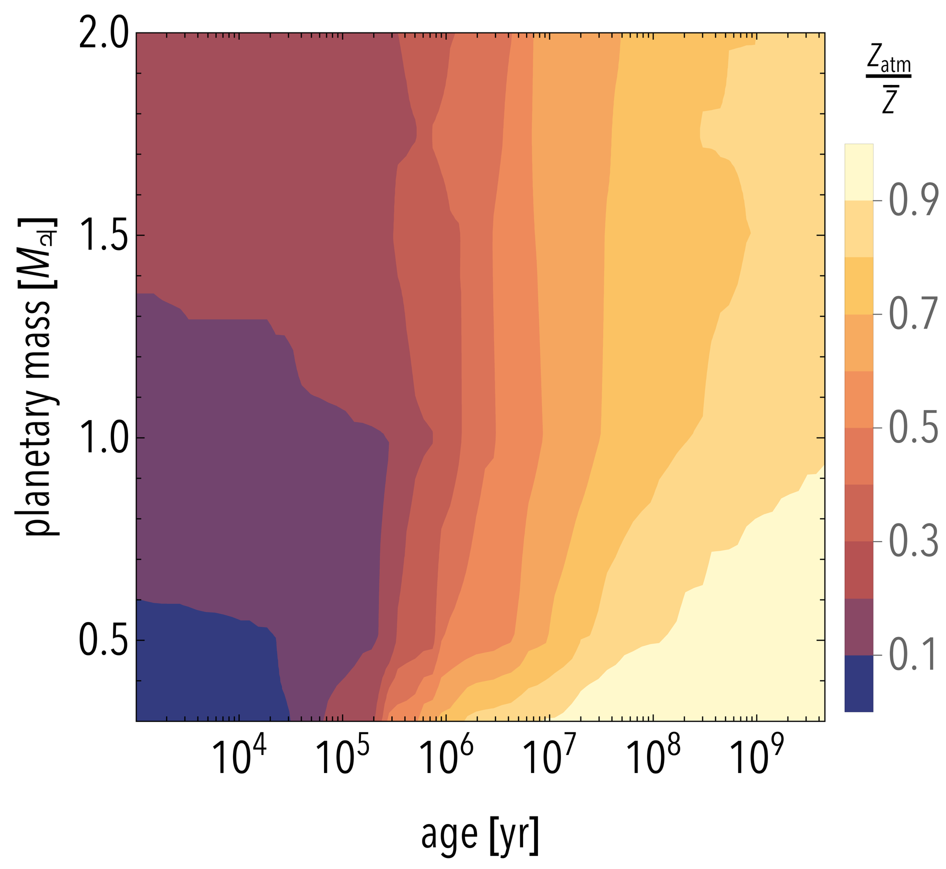


Fig. 3. Time evolution of atmospheric-to-bulk heavy-element mass fraction for a range of planetary masses at a fixed entropy of $S = 10\ k_B m_u^{-1}$.

Low mass planets mix more

- We simulated planetary masses between 0.3 and 2 M_J for the same primordial entropy.
- Low mass planets mix more and more rapidly
- High mass planets start with a higher fraction of metals in their envelopes, but mix less overall.
- Entropy might increase with planetary mass, potentially reversing this trend.

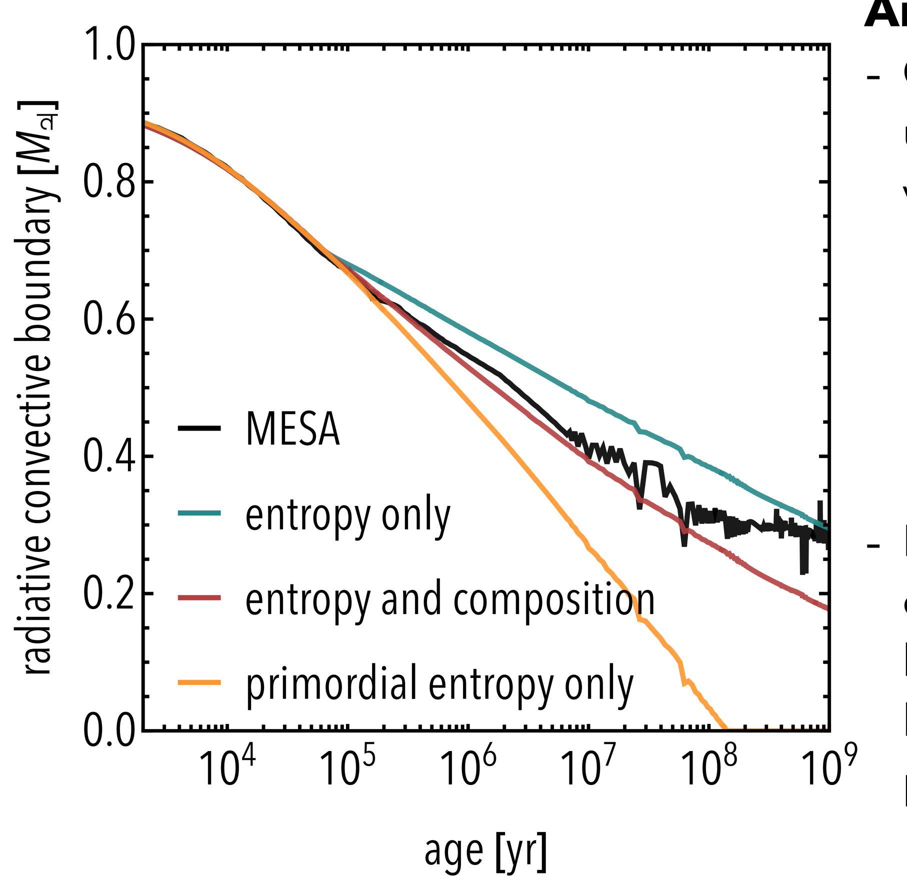


Fig. 4. Time evolution of the radiative-convective boundary from MESA and the analytic model under three different scenarios.

Analytic Modeling

- Convective mixing can be analyzed using entropy as a thermodynamic variable, leading to a stability criterion

$$\frac{ds}{dr} - \sum_{i=1}^{N-1} \left(\frac{\partial s}{\partial X_i} \right)_{P,\rho,\{X_{j\neq i}\}} \frac{dX_i}{dr} > 0$$

- Integrating this criterion provides an entropy budget that determines the location of the radiative-convective boundary (RCB), which in turn predicts the extent of mixing

$$\frac{\delta S}{M - m_{\mathrm{RCB}}} = \Delta s(m_{\mathrm{RCB}}) + \delta s_{X,Z}(m_{\mathrm{RCB}})$$

Conclusions

Atmosphere ≠ Bulk

For planets with steep composition gradients, the atmospheric heavy-element mass fraction can be drastically different from the bulk composition.

Entropy: the driver of convective mixing

The higher the primordial entropy (i.e., the formation heat) the more the planet mixes.

Mass trend depends on entropy trend

For the same primordial entropy, low mass planets mix more efficiently than high mass planets. If the primordial entropy increases with mass, this trend might reverse.

Interested?

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Paper

References

Jupiter icon from flaticon.com.

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