Rocky worlds: What do a planet's orbital parameters tell us about its mantle state?

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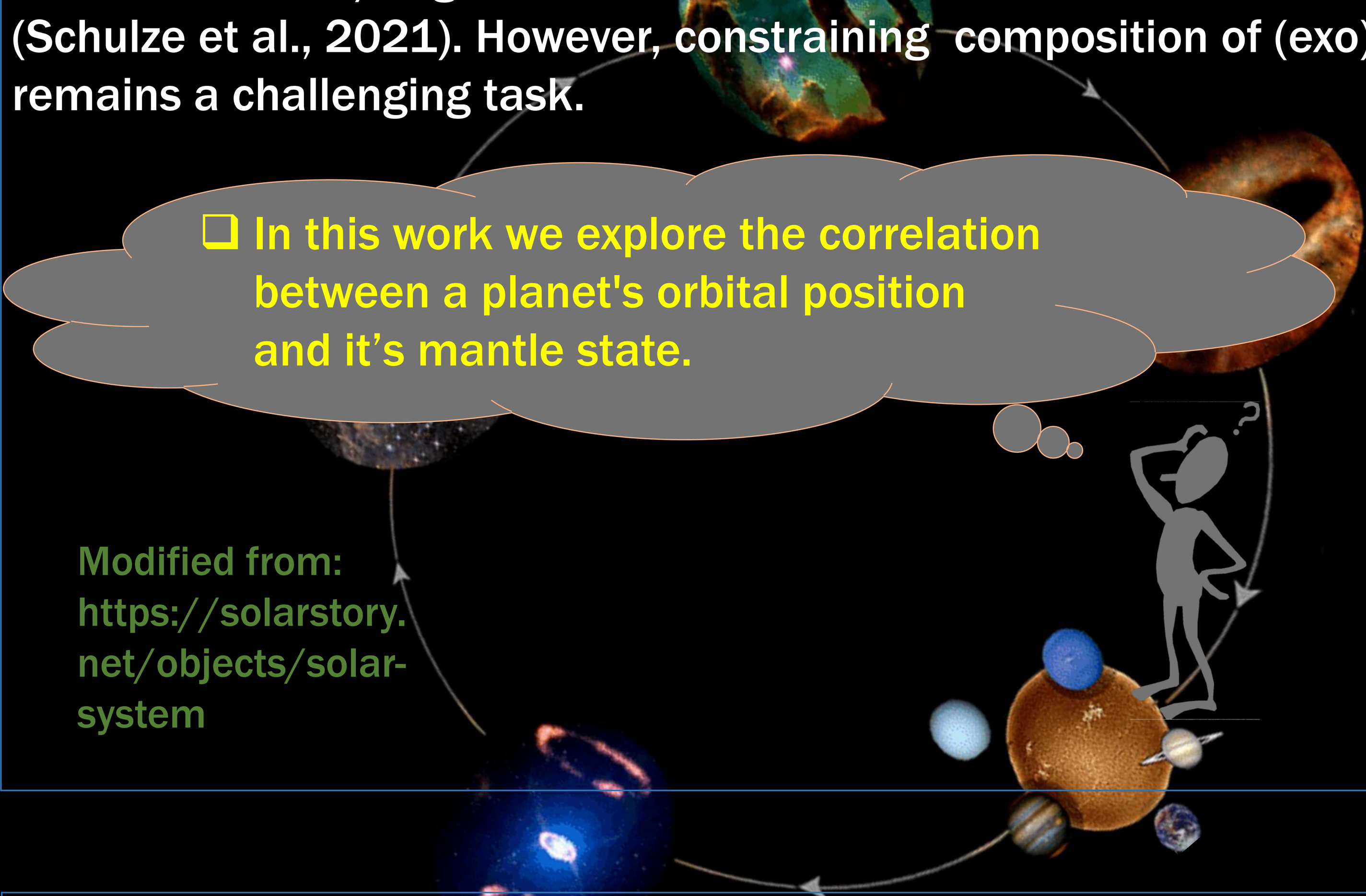
Abstract

Rocky (exo)planets can be classified based on their mantle viscous state. The mantle viscosity influences the efficiency of convection and heat loss of the planet, altering the outgassing rate. Low viscous planets are hypothesized to have strong volcanic activity reshaping the surface and changing the atmosphere. This can be seen in other almost-similar rocky bodies such as Io, one of Jupiter's Galilean moons, and would be expected of young rocky exoplanets. Whereas, the intermediate viscous planets have less vigorous resurfacing. They experience occasional complete mantle-overturn to slow-moving plate tectonics driven by mantle convection. As a result, their atmospheres vary little or smoothly across time. High viscous planets can be seen as inert, with little or no mantle convection. Moreover, hotspot volcanism might still occasionally contribute to outgassing, producing a less dominant atmosphere. Through this relationship, a planet's atmosphere could reveal information about the evolution of a planet's interior and surface. However, we rely on primary observables to characterize (exo)planets. So, is there a correlation between a planet's orbital position and mantle viscosity? The answer to this question would aid in the characterization of rocky exoplanets, which is the focus of this work.

To study the relationship between a planet's mantle viscous state, interior composition, and structure. We use Perple-X to generate mineral physics properties, and Burnman to build a 1-dimensional depth profile of the planet. From this, 2-dimensional annulus compressible convection models are developed using ASPECT. And, exploring the stagnant lid, the episodic lid, and the tectonic convection regimes. We consider the anelastic liquid approximation (ALA). An isoviscous profile results in a hot mantle but can be used for first-order approximations of mantle dynamics without a crust. However, the presence of crust requires for temperature-dependent stratified viscosity profile for the deeper mantle to allow for the cooling of the mantle. The stratification structure of the mantle is determined by the temperature sensitivity of the mineral phases present in the depth profile of the mantle. There is an observed trend of iron mass fraction in the mantle (X_{fem}) increasing with increasing distance from the sun. The iron number in the mantle (X) for Mercury $X = 0.05$, Venus $X = 0.08$, Earth $X = 0.1$ and Mars X= 0.12 . Thus, X_{fem} is highly dependent on the orbital position and dictates the viscosity profile of the mantle of the given planet. Thus, a planet's mantle viscous state is correlated to it's orbital position.

Introduction

Rocky planets are predominantly made of Fe and MgSiO3. This is a reflection of the major rock building blocks (Fe, Mg, and S) in our Sun. Earth, Mars and Venus have a Fe / Mg molar ratio to within ~ 10 of the solar abundance (Schulze et al., 2021). However, constraining composition of (exo)planets remains a challenging task.



Modified from: https://solarstory.net/objects/solar-system

Building Planetary interior

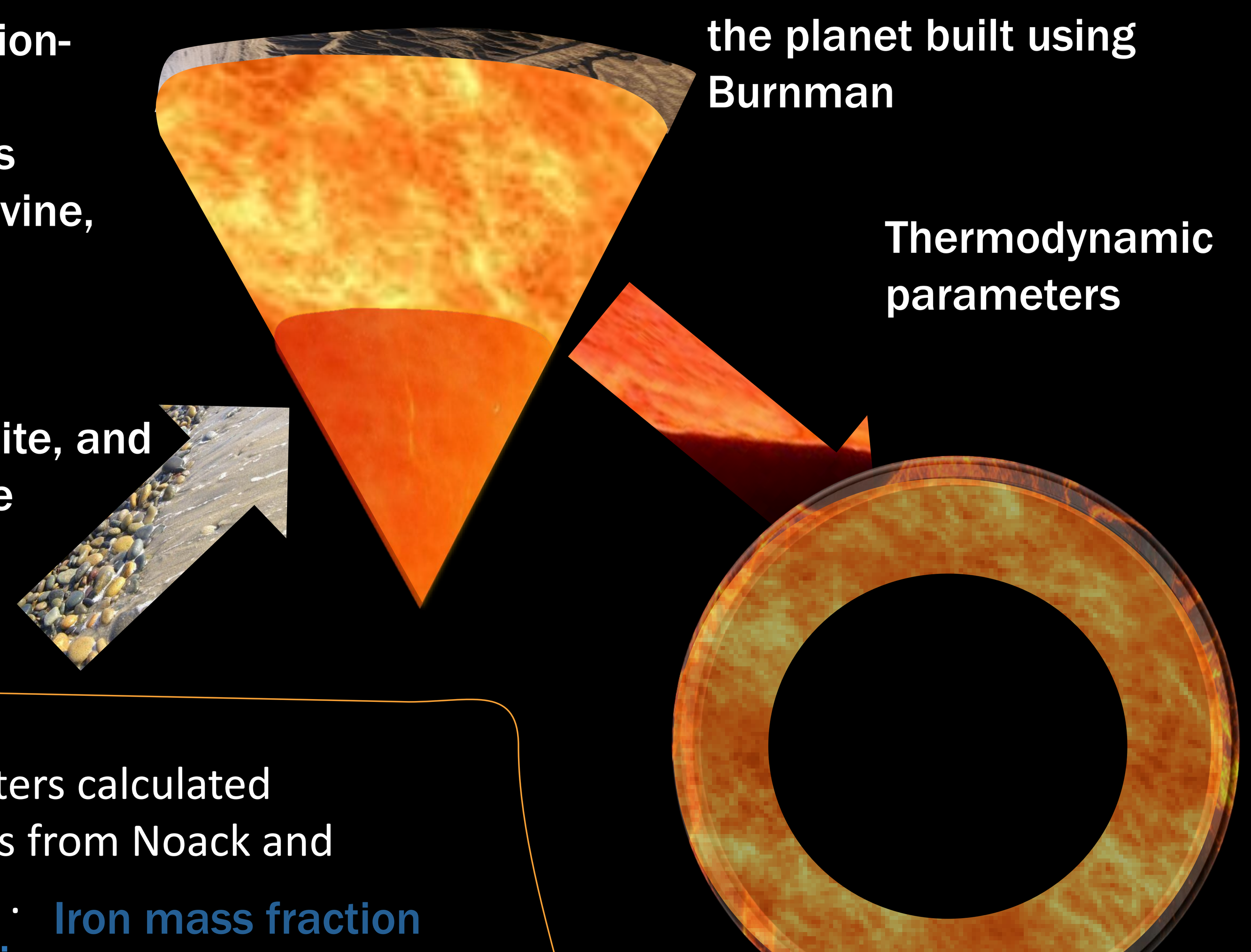
❑ We explore the thermal evolution of the mantle of planets with Earth, Mars, and Venus-like composition. With a focus on silicate composition.

❑ Bulk composition- Perple_X

❑ Mineral phases considered: olivine, wadsleyite, ringwoodite, bridgmanite, magnesiowüstite, and post-perovskite

Internal structure of the planet built using Burnman

Thermodynamic parameters



❑ Planet parameters calculated using equations from Noack and Lasbleis (2020) .

Core mass fraction — Iron mass fraction — Iron mass fraction in the mantle

$$X_{cmf} = \frac{X_{Fe} - X_{Fem}}{1 - X_{Fem}}$$

Parameter	Earth	Mars	Venus
X_{Fe}	0.35	0.28	0.32
X_{cmf}	0.30	0.15-0.30	0.22-0.32

A 2-dimensional annulus compressible mantle convection model developed in ASPECT, considering :

❑ Constant temperature boundary conditions.

❑ Stagnant-lid convection regime.

❑ Anelastic liquid approximation (ALA) formulations.

❑ Viscosity profile defined by:

$$\eta(z,T) = \eta_r(z)\eta_0 exp\left(-A\frac{T - T_{ad}}{T_{ad}}\right)$$

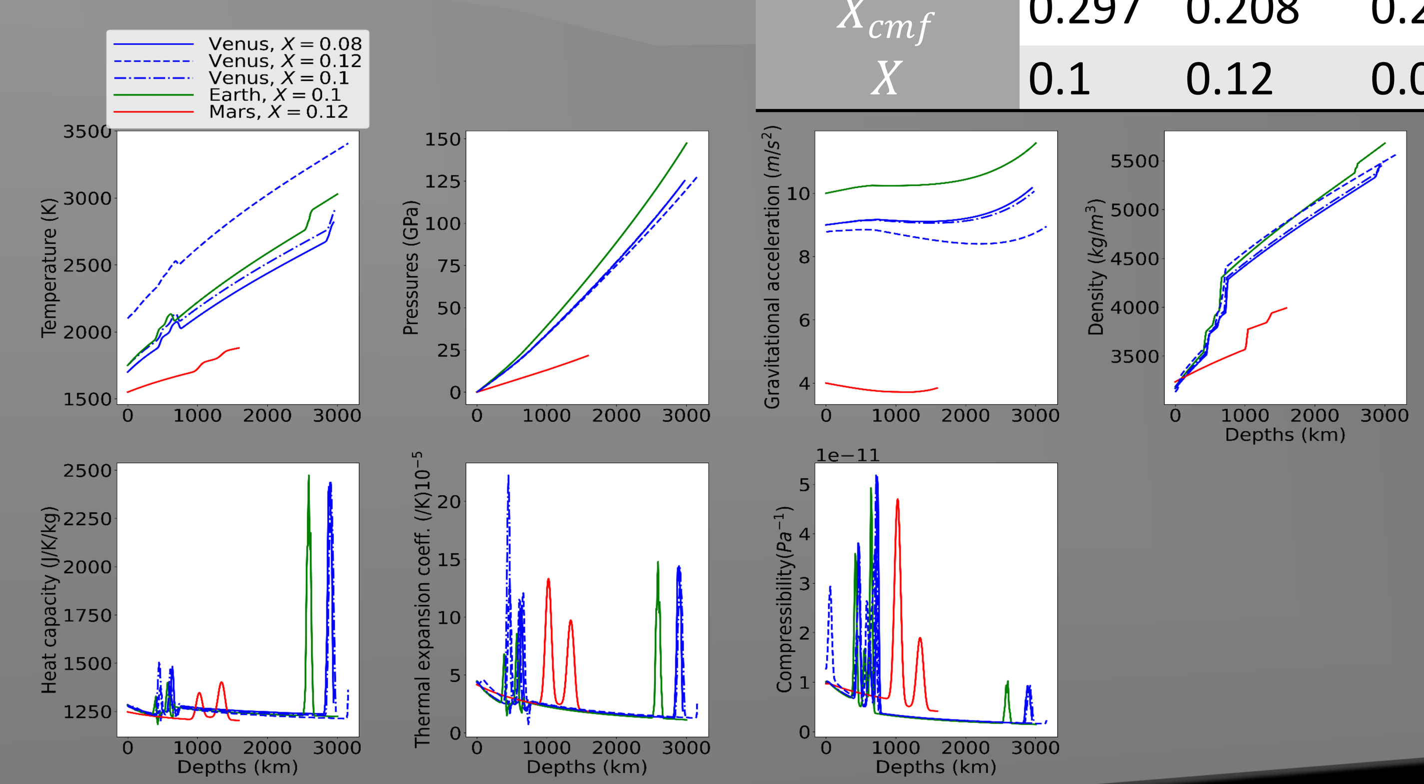
thermal viscosity prefactor

Iron number and the mantle state

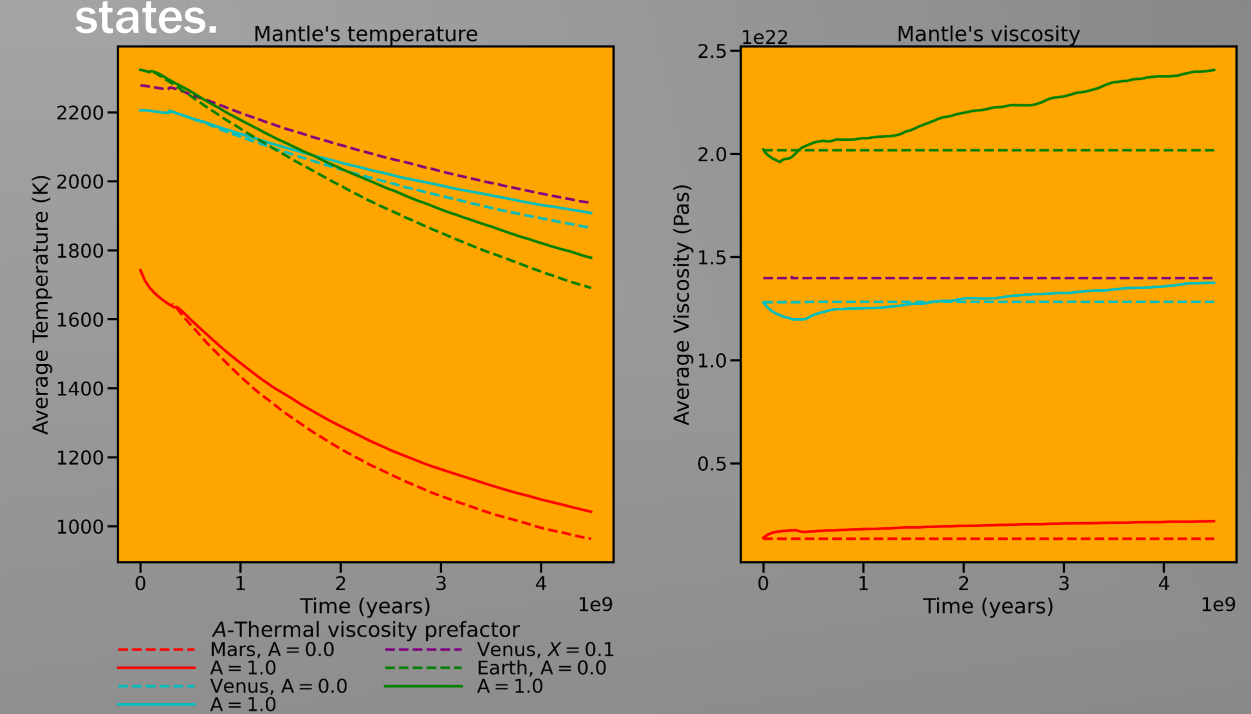
❑ X is the iron number in the mantle.

❑ Thermodynamic parameters

Calculated parameters			
Parameter	Earth	Mars	Venus
X_{cmf}	0.297	0.208	0.28
X	0.1	0.12	0.08



❑ Temperature and viscosity evolution for given mantle states.

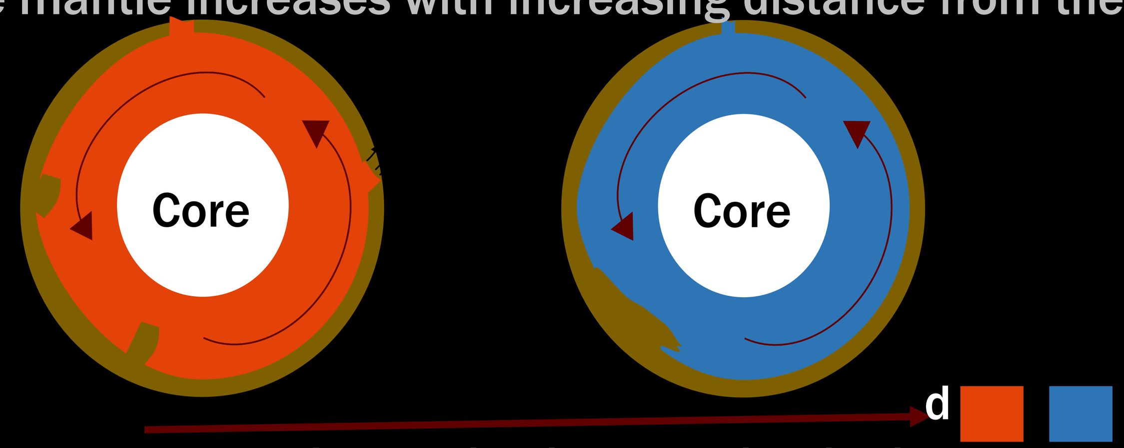


❑ Increasing iron number in the mantle results into increase in viscosity i.e. comparing (--) to (--)

Conclusion

❑ Mantle's structure significantly influences a planet's internal thermal state.

❑ Iron number in the mantle increases with increasing distance from the star.



Increasing iron number in the mantle, increasing viscosity

References

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