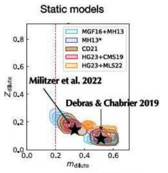
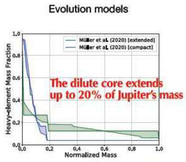
What's the extent of the dilute core?

- Reconciling static models that fit the gravity data with evolution models that model convective mixing is important but remains a challenge.



Howard et al. 2023a

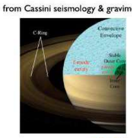


Müller et al. 2020

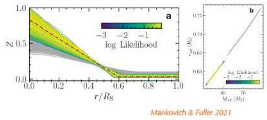
A dilute core also in Saturn?

- Interior models of Saturn also suggest the presence of a dilute core. It is even more constrained thanks to ring seismology.

from Cassini seismology & gravimetry



Fuller 2014

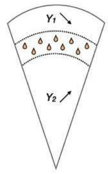


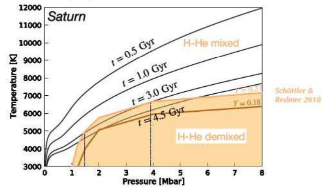
Mankovich & Fuller 2021

- Is the dilute core similar as in Jupiter?

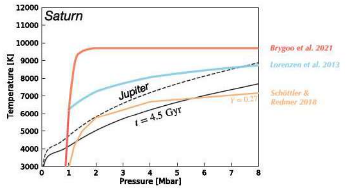
Helium rain in Jupiter and Saturn

- Evolution models coupled with a H-He phase diagram can provide information about the planetary interiors.
- Helium becomes immiscible with metallic hydrogen.





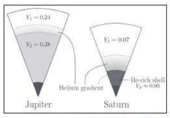
But phase diagrams are uncertain



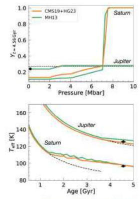
- A recent experiment suggests much higher demixing temperatures. Relevant for exoplanets?

A dichotomy in the internal structures of Jupiter and Saturn

- He rain is modest in Jupiter but drastic in Saturn.



Mankovich & Fortney 2020

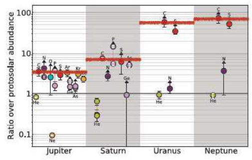


- Accounting for these internal processes is important. They affect what is observed in the atmosphere.

Howard, Müller, Helled 2024

One important problem remains

- How to reconcile interior models with atmospheric measurements?



- Jupiter models can barely exceed a solar atmosphere
- Saturn models can reach 4x solar
- Is the atmosphere decoupled from the outer envelope?

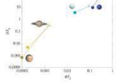
Howard et al. 2023b

- Do we have the wrong EOS?

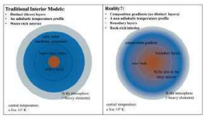
Xie, Howard, Mazzola 2025
Cozza, Howard et al. 2025

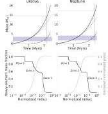
Uranus and Neptune

- Uranus and Neptune have only been visited by Voyager 2…
- The decadal survey recommended a future mission to Uranus (2040? 2050?)
- Only J2 and J4 have been measured and with larger uncertainties.



- Composition gradients also in the ice giants?

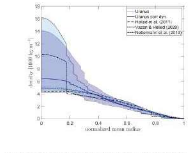


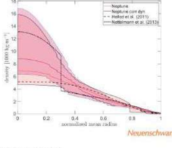


Valletta & Helled 2022

Empirical models

- Given the uncertainties and the lack of data, it can be interesting to start by looking what density profiles fit the gravity data. And retrieve composition afterwards.



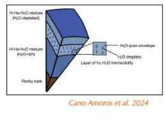


Neuenschwander & Helled 2022

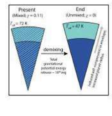
- H-He mass is probably no more than 3 or 4 earth masses.
- The rest is highly uncertain. Ices? Rocks? Which ices? Which rocks?
- Are they « ice » giants?

Phase separations in Uranus and Neptune

- Heat fluxes are different for both planets. This might be explained by hydrogen-water demixing and both planets being in a different stage of this process.



Cano Amoros et al. 2024

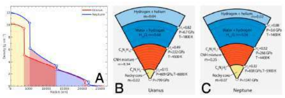


Bailey & Stevenson 2021

- The water content in Uranus' atmosphere might be more depleted than in Neptune.

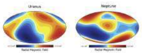
Phase separations in Uranus and Neptune

- Phase separations between ices (water, ammonia, methane)



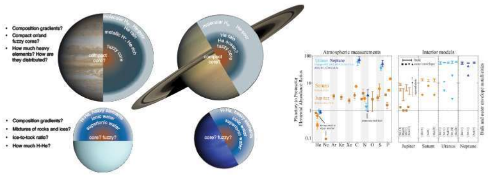
Militzer 2024

- Their magnetic fields are non-dipolar. Dynamo models imply a convective region (ionic water?) in the outer envelope.



- The internal structure and composition of Uranus and Neptune remain uncertain. Understanding the thermodynamical properties of their components is important. We need better gravity data and atmospheric composition measurements.

Summary



Helled & Howard 2024

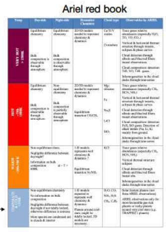
Outline

Giant planets in the solar system vs in exoplanetary systems

	Mass	Radius	T_{eq}
Jupiter	$318\ M_\oplus$	$11\ R_\oplus$	112 K
Saturn	$95\ M_\oplus$	$9.5\ R_\oplus$	83 K
Uranus	$14.5\ M_\oplus$	$4\ R_\oplus$	59 K
Neptune	$17\ M_\oplus$	$3.9\ R_\oplus$	46 K

- No super-Earth, no sub-Neptune, no hot-Jupiter in the solar system.
- ARIEL will observe ~1000 exoplanets from super-earths to Jupiters, from temperate to very hot.

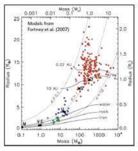
Ariel red book



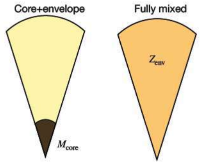
Solar system giant planets are here ⟶

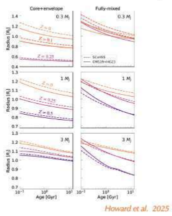
Giant exoplanets

- For exoplanets, our main constraints are radius and mass. We don't have gravity data.
- We sometimes have the age of the systems, which is useful to constrain evolution.
- Since a decade, we are getting atmospheric data.
- Mass-radius diagram:



Giant exoplanet models



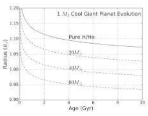


Howard et al. 2025

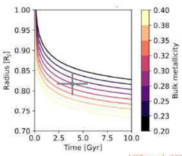
- We define the **bulk metallicity** by : $Z = M_Z/M_p$
  $Z = M_{core}/M_p$ for CE $\quad$ $Z = Z_{env}$ for FM
- The presence of a dilute core could store heat and release it later. *Leconte & Chabrier 2012*

Giant exoplanet models

- The bulk metallicity is constrained given cooling tracks and radius, age and mass measurements:



Thorngren et al. 2016

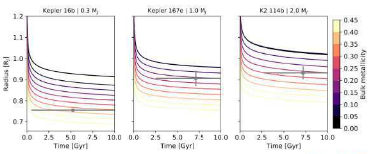


Müller et al. 2023

- Accurate measurements are needed.

Importance of age

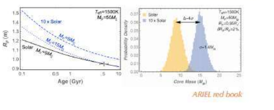
- PLATO will measure age with accuracy $(\sigma_{age} < 10\%)$



Müller et al. 2023

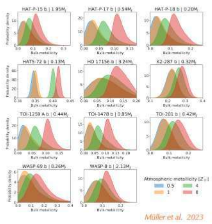
Importance of atmospheric composition

- Atmospheric measurements can lift some degeneracies.



ARIEL red book

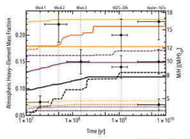
- The bulk metallicity can be inferred using MCMC and drawing samples from the observed mass, radius, age, equilibrium temperatures, atmospheric metallicity within their uncertainty range.



Müller et al. 2023

Importance of atmospheric composition

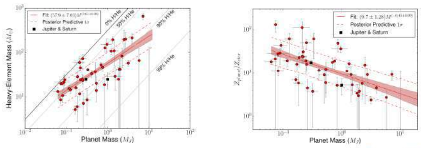
- A good understanding of convective mixing can link the measured atmospheric composition with the planetary primordial state.



Knierim & Helled 2024

Can we identify trends?

- Mass-Metallicity relation for giant planets with T_{eq} < 1000K.

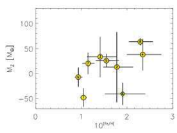


Thorngren et al. 2016

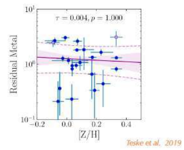
- Large spread shows the diversity of exoplanets.

Link between planet and host star composition

- Is the planet metallicity related to the host star metallicity?



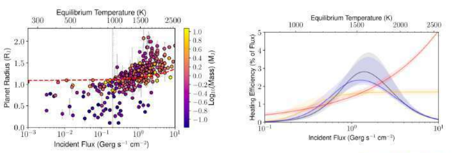
Guillot et al. 2006



Teske et al. 2019

Inflated hot Jupiters

- Radius anomaly for planets with T_{eq} > 1000K



Thorngren & Fortney 2018

- Possible mechanisms (coupled to the stellar heating): e.g. vertical mixing, Ohmic dissipation…

Fortney et al. 2020

Outline

1. Why study interiors of planets?
2. What are the building blocks of planets?
3. How to study planetary interiors?
   - How to make a model?
   - What observational constraints?
4. What do models predict?
   - Results for Jupiter, Saturn, Uranus and Neptune
   - Results for exoplanets
5. **Conclusion**

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Conclusion

- Interior and evolution models solve a set of equations. They are based on equations of state and rely on a good understanding of the heat transport mechanisms.
- Planetary interiors is a multiphysical problem.

- Interior models should be linked to evolution and formation models, for a unified picture.
- The knowledge gained from the solar system should be applied to exoplanets. Identifying trends in the numerous exoplanets can provide information on the formation mechanisms.
- Current (JWST) and upcoming (PLATO, ARIEL) missions will provide radius, mass, age and atmospheric composition measurements of exoplanets that will improve our understanding of planetary interiors.

- Solar system, exoplanets and high-pressure physics communities should work together.

Conclusion

Fighting for planetary interiors!