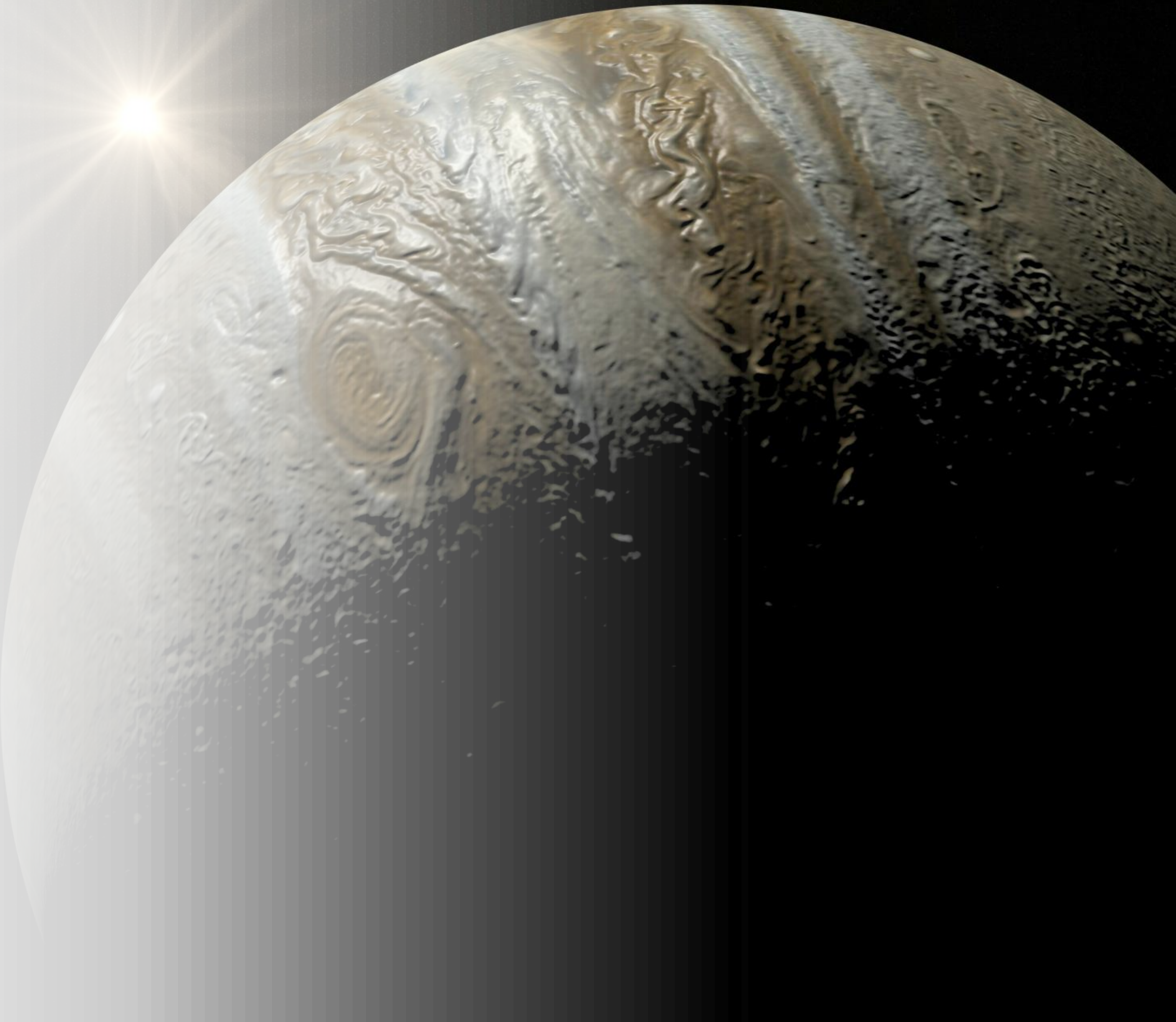
From Compact to Fuzzy: The New Interior Paradigm for Jupiter, Saturn, and Gas Giant Exoplanets



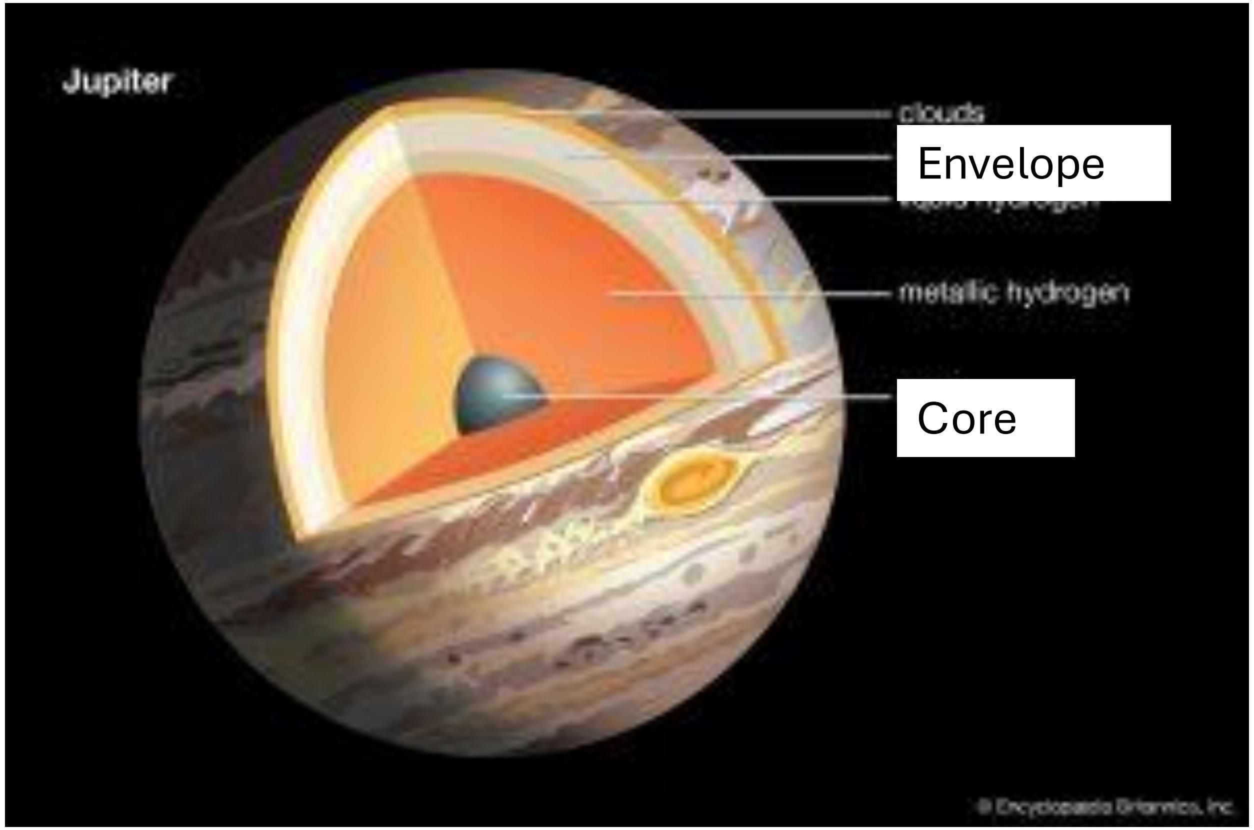
Ankan Sur

Earth, Planetary, and Space Sciences

UCLA

ExSoCal 2025

Planet Structure and Evolution: old picture

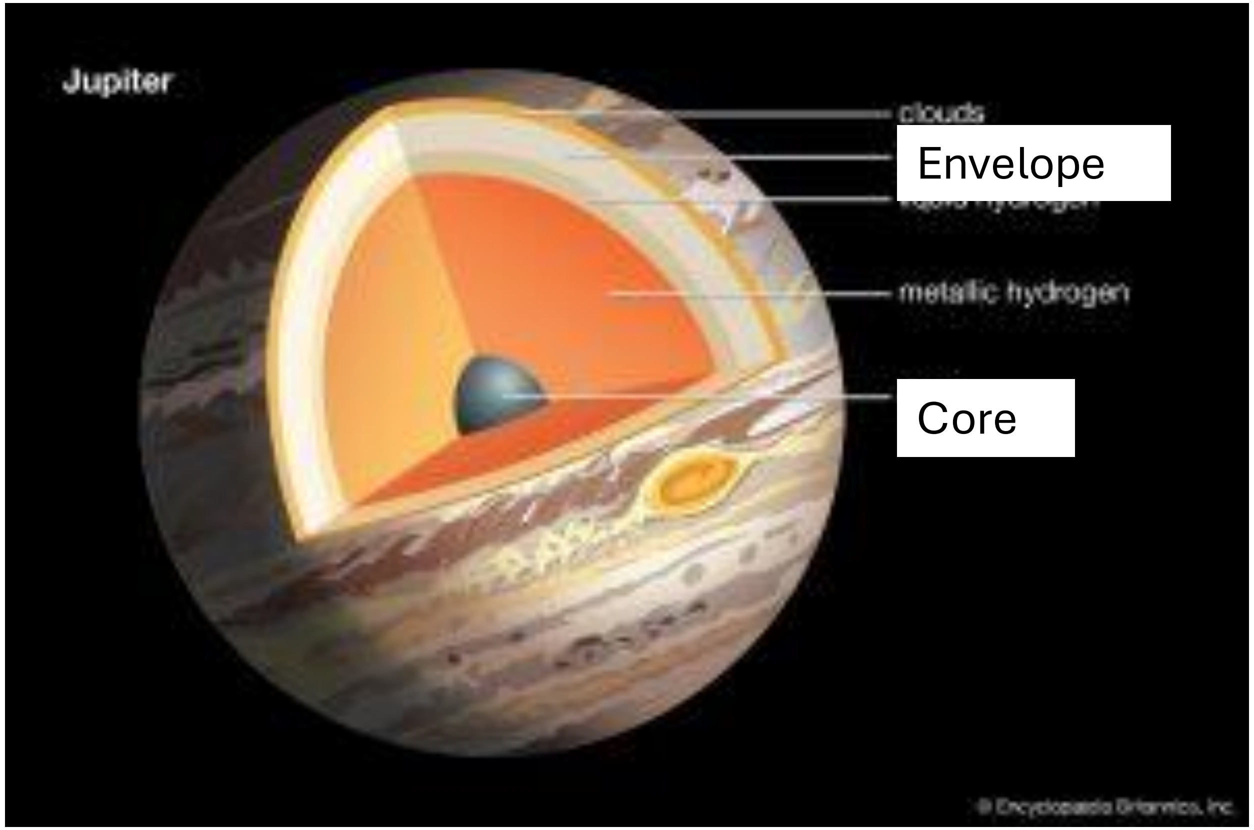


- Planet consists of a

  Rocky Core + Hydrogen-Helium Envelope

- Gives the right radius

Planet Structure and Evolution: old picture



Adiabatic Models: TdS/dt = -dL/dM

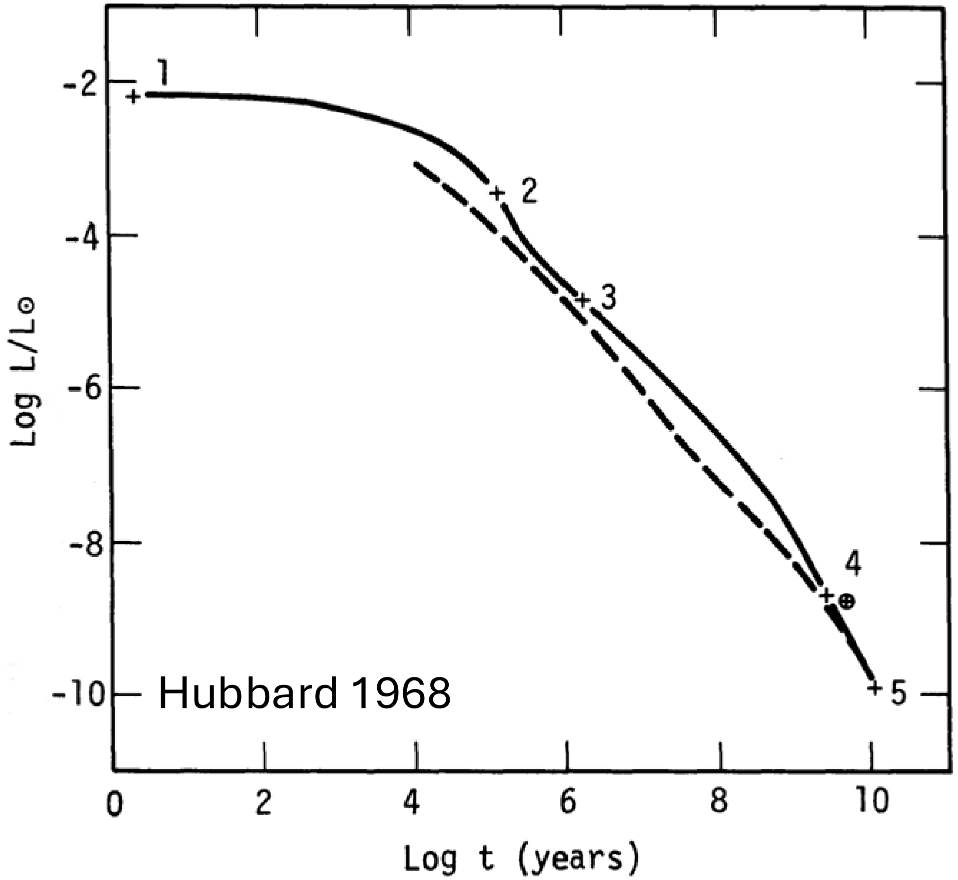
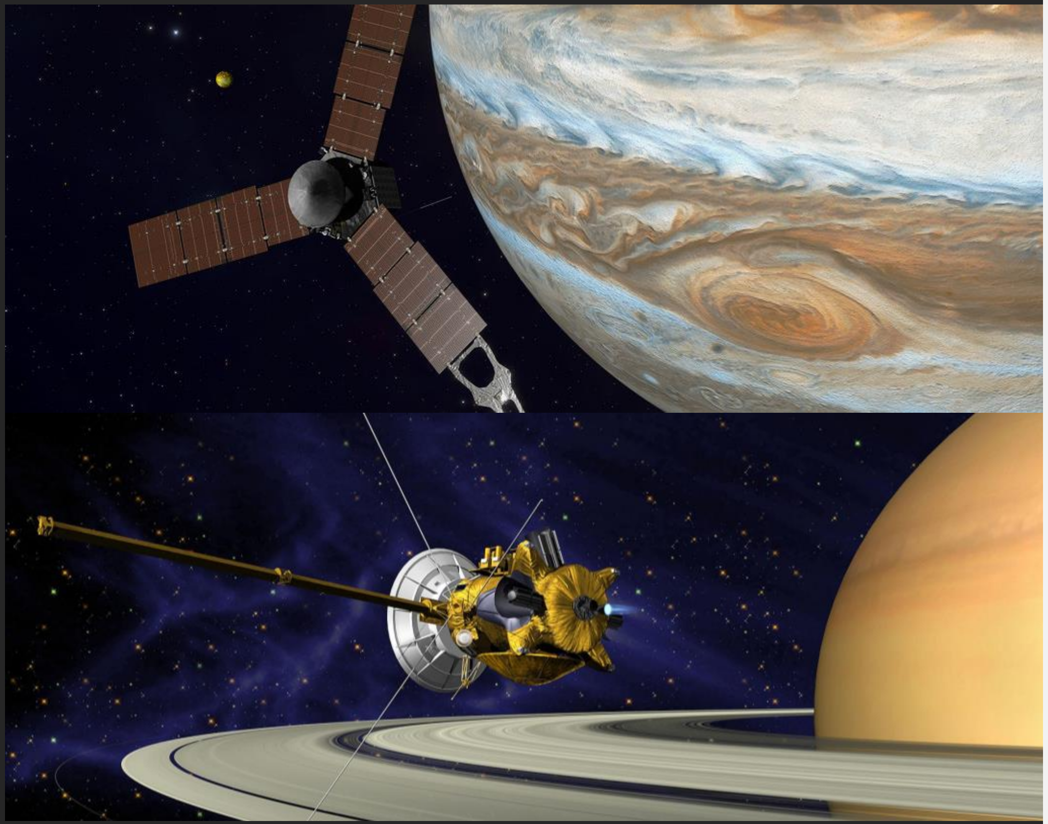


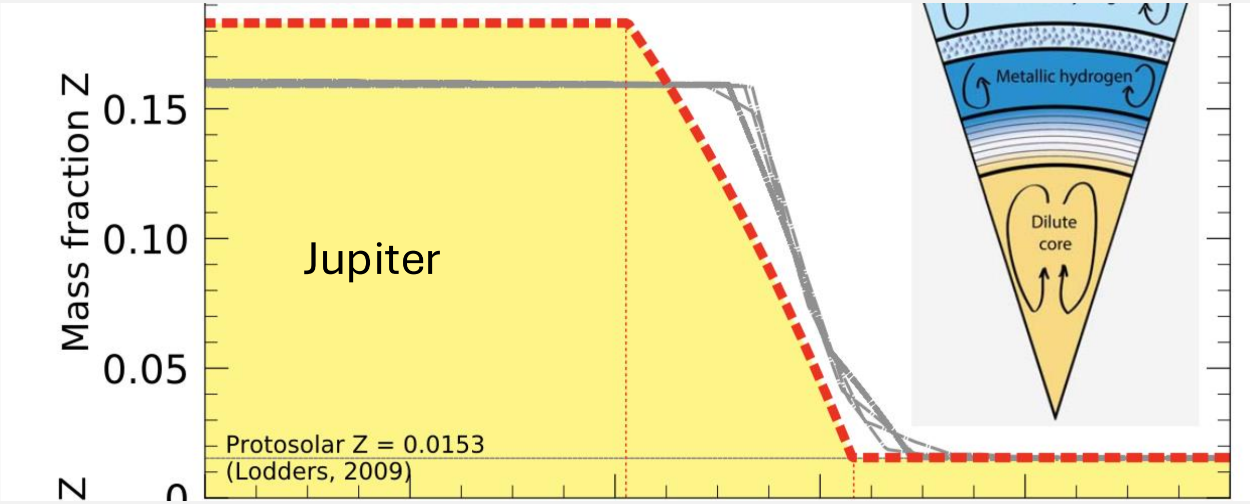
FIG. 3.—Time dependence of luminosity for the S1 standard sequence, with epochs 1 to 5, the Jovian luminosity and the hydrogen sequence shown as in Fig. 2.

Planet is fully convective and homogeneous.
Able to explain the luminosity of Jupiter.

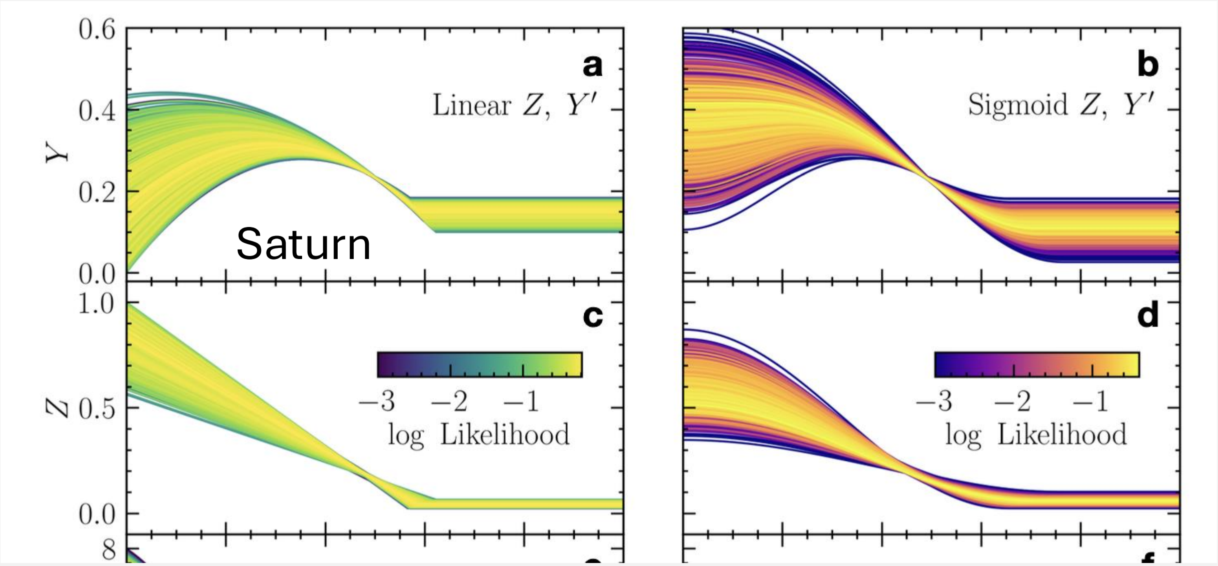
Juno and Cassini: Gravity data, Seismology



Fuzzy Cores



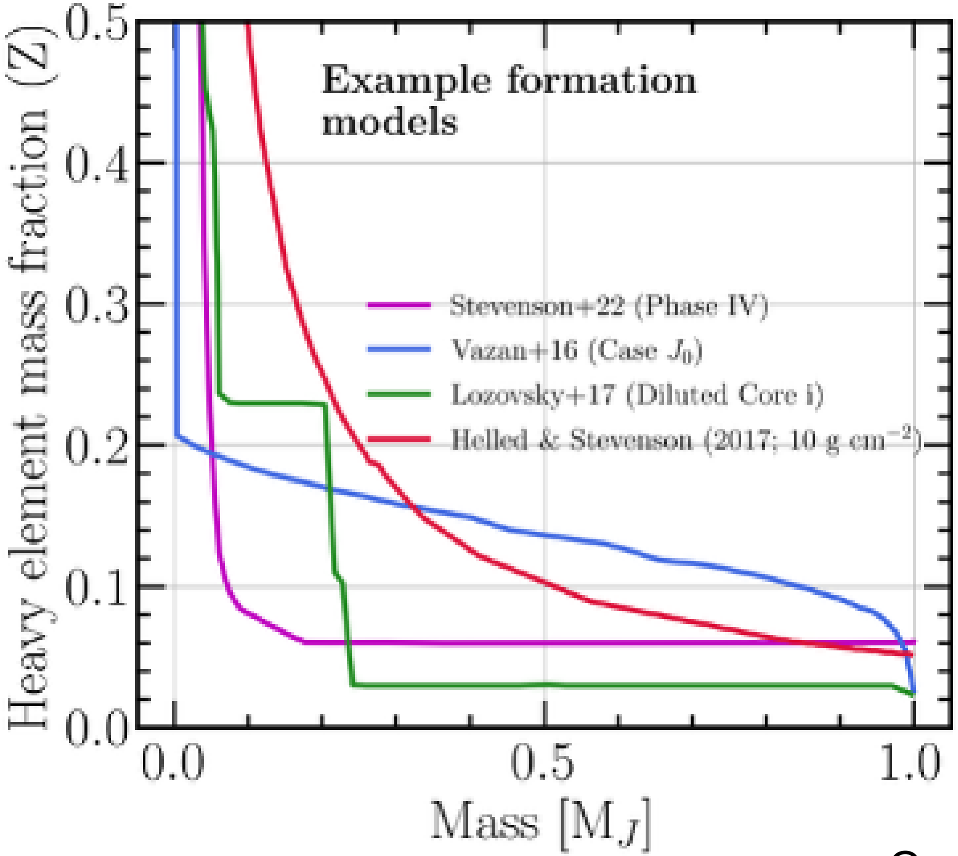
Militzer (2022)

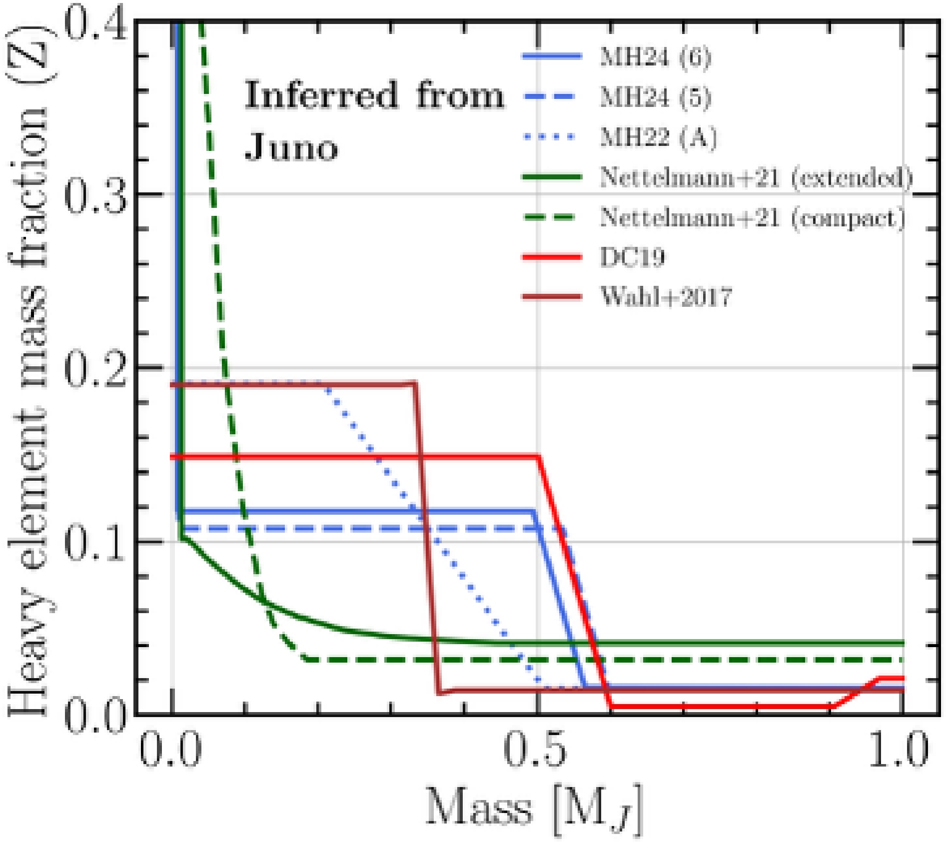


Mankovich&Fuller 2021

From Formation to Current age

Jupiter

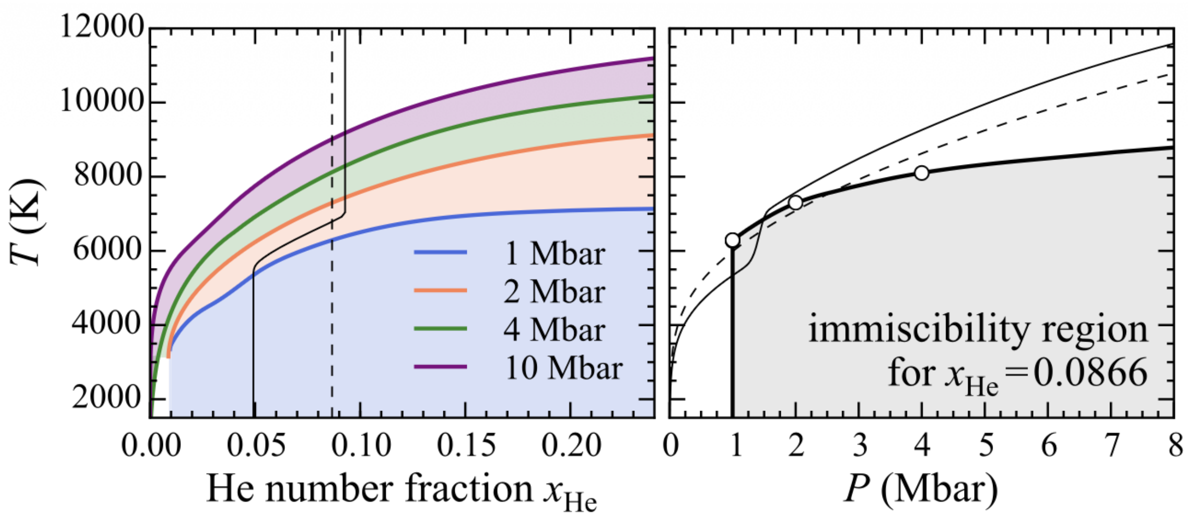




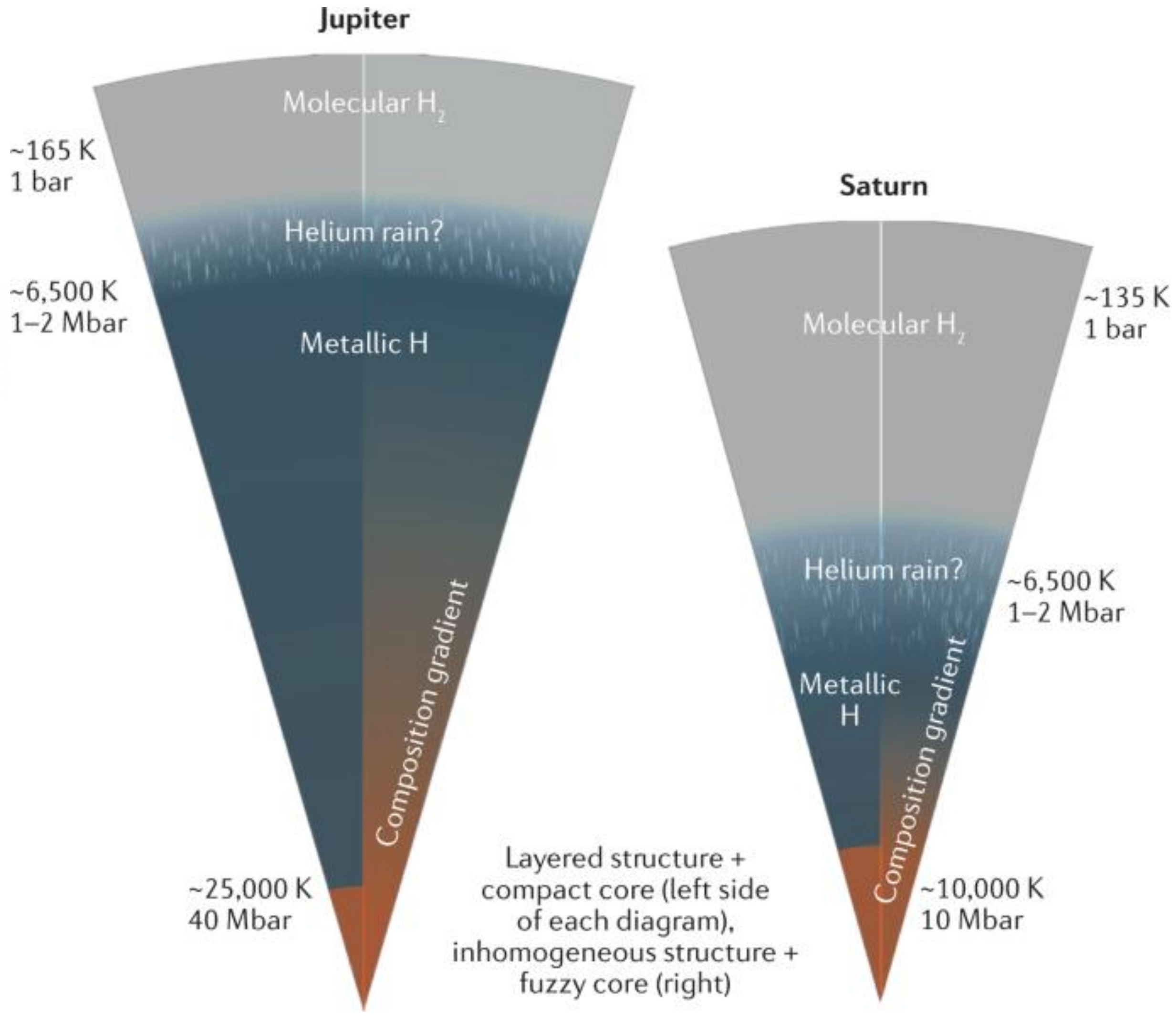
Compiled by Tejada Arevalo

Demixing in Giant Planets: Helium Rain

Hydrogen-Helium miscibility



Lorenzen et al (2009, 2011)



Credit: Ravit Helled

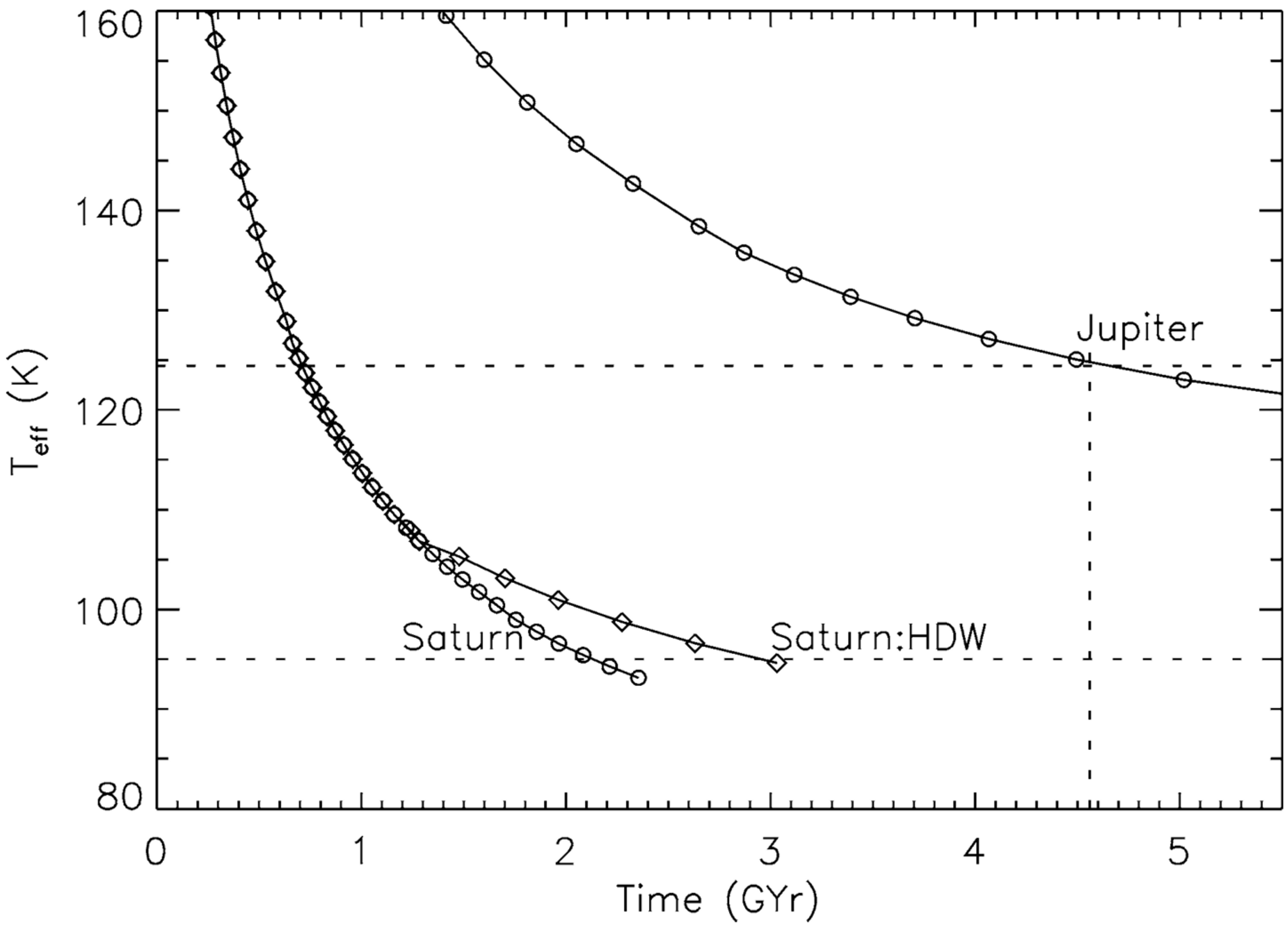
Planet Structure and Evolution: Adiabatic and Inhomogeneous Evolution

- Hydrogen-Helium demixing: helium rain

- Explain Saturn's luminosty (Stevenson & Salpeter 1977)

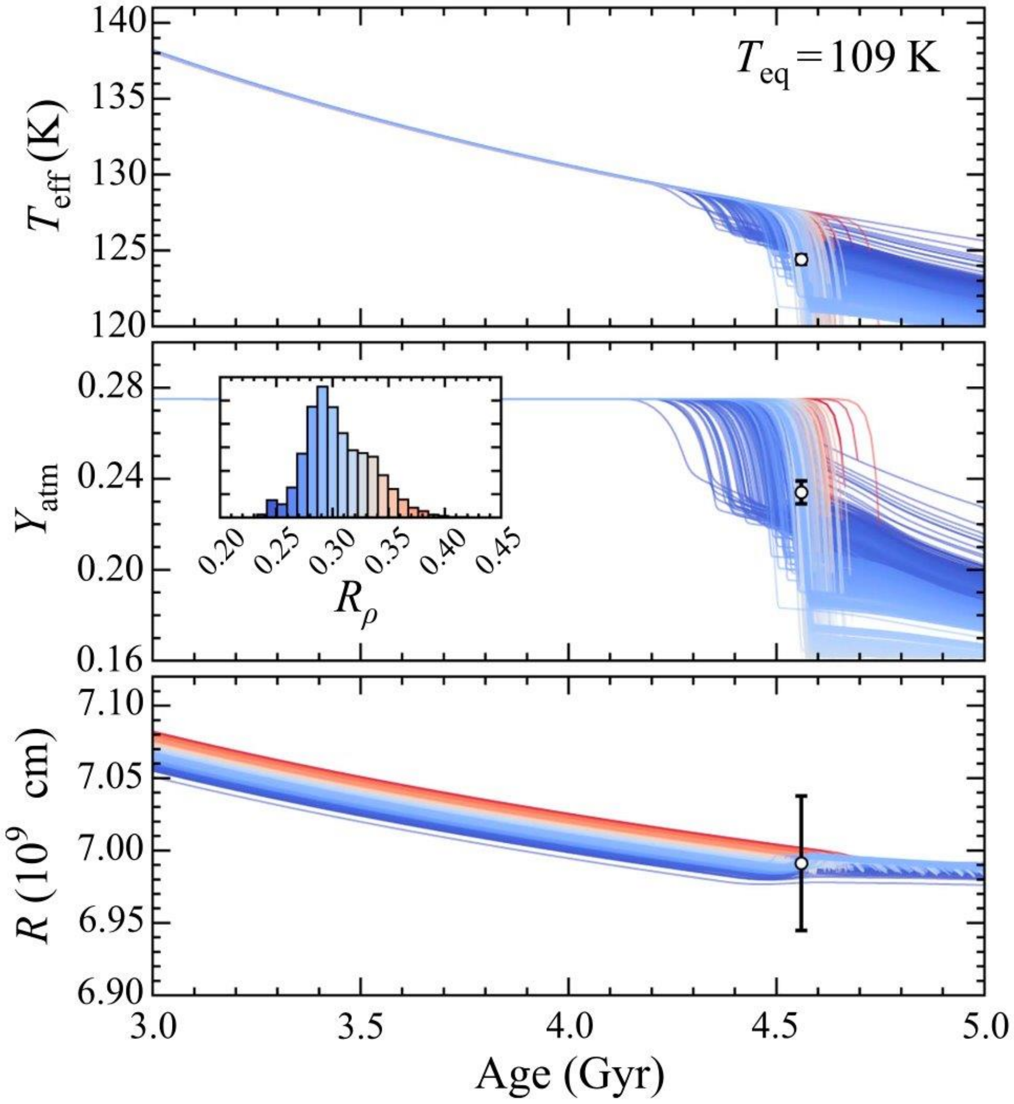
- Explain Galileo observation: Y = 0.234 +/- 0.005

Fortney & Hubbard 2003



Jupiter and Saturn's Structures and Evolution: Adiabatic and Inhomogeneous Evolution

Mankovich & Fortney 2016



- Evolution with helium rain
- Superadiabatic temperature gradients
- Used Bond Albedo=0.5
- Saturn's Yatm=0.07

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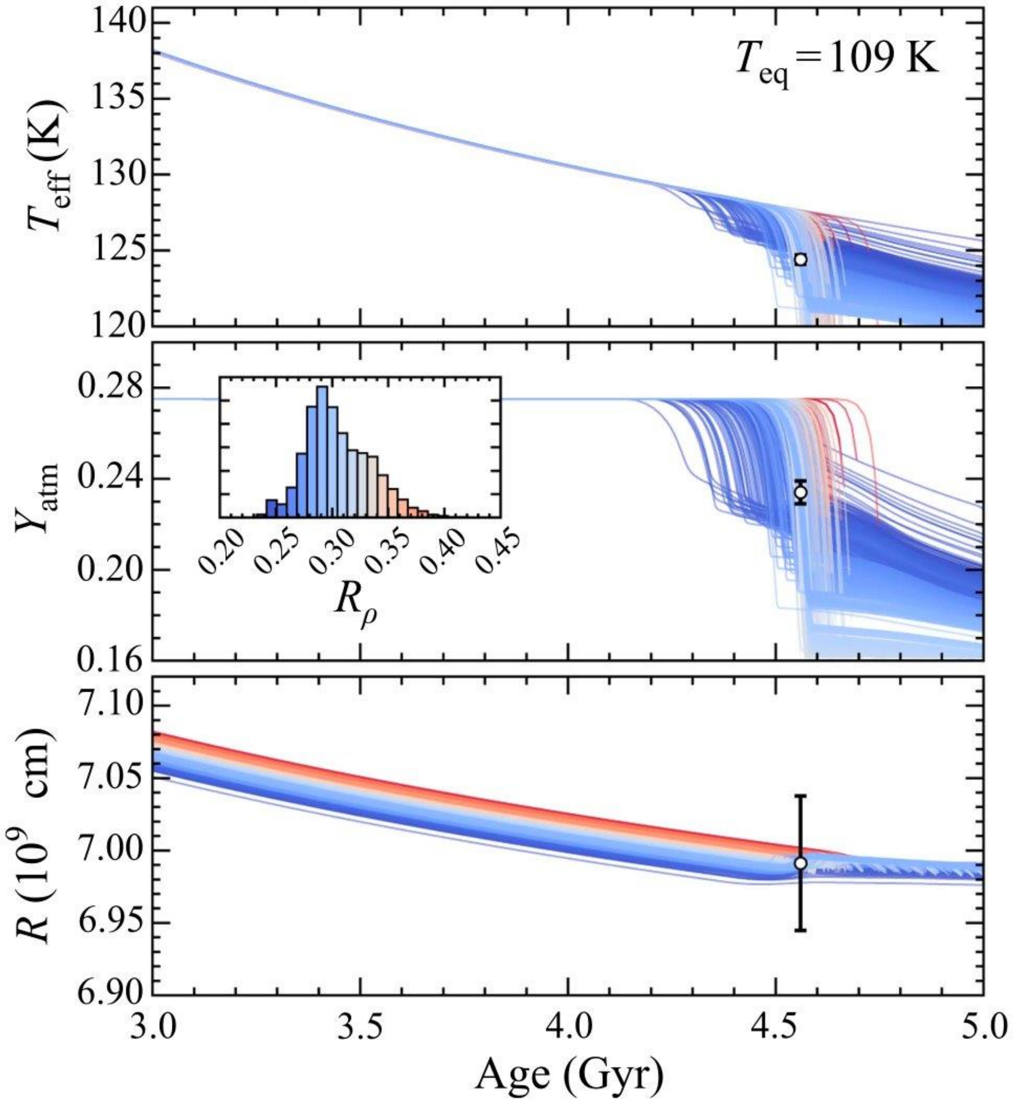
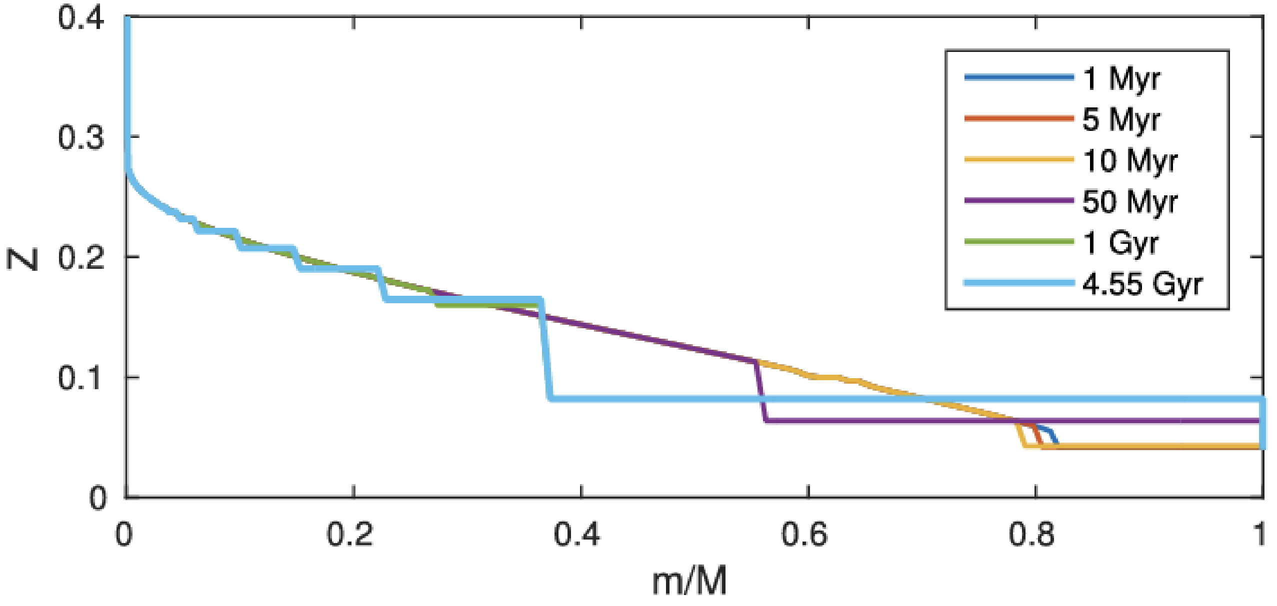


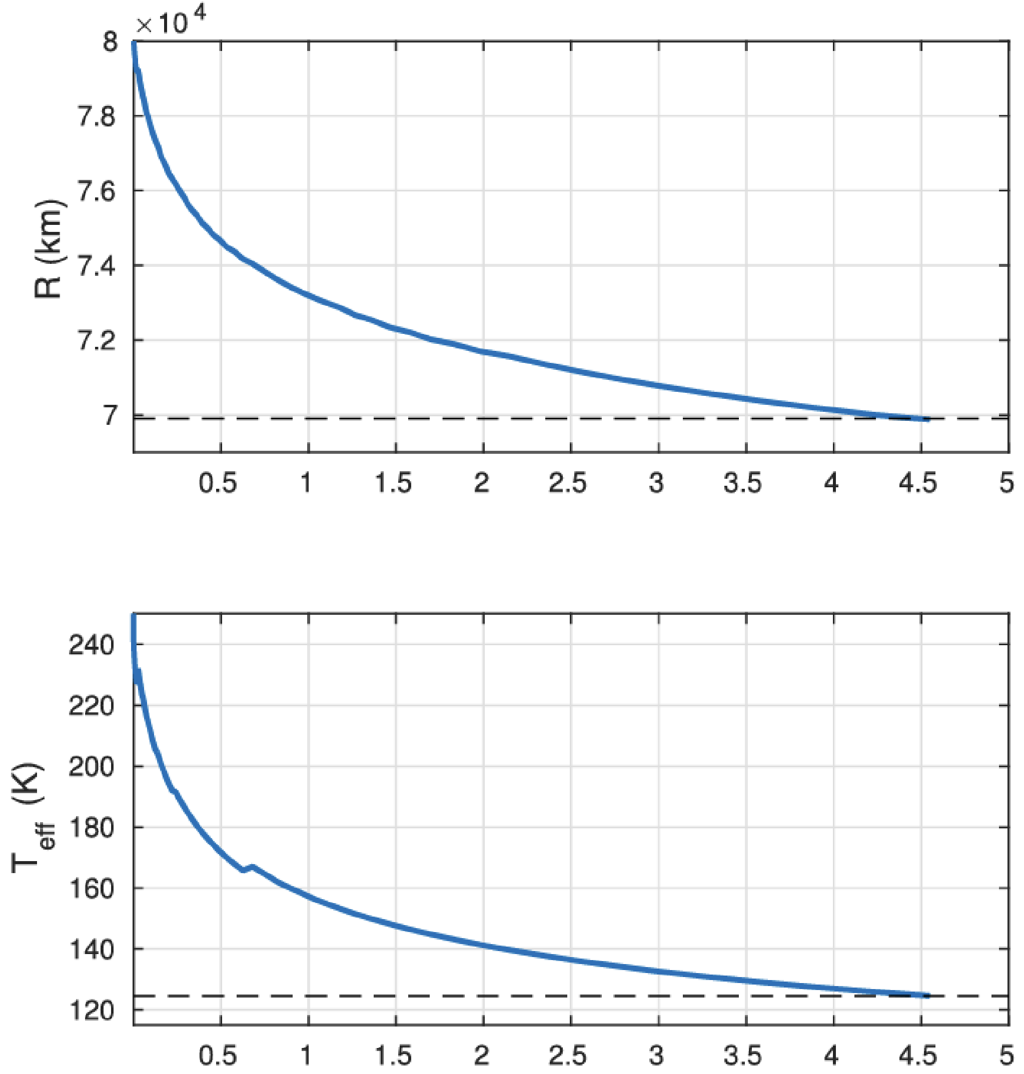
Problem: Did not include Fuzzy Cores

Jupiter Structure and Evolution: Non-adiabatic and Inhomogeneous Evolution

Vazan, Helled, Guillot (2018)

Evolution of Jupiter with composition gradients





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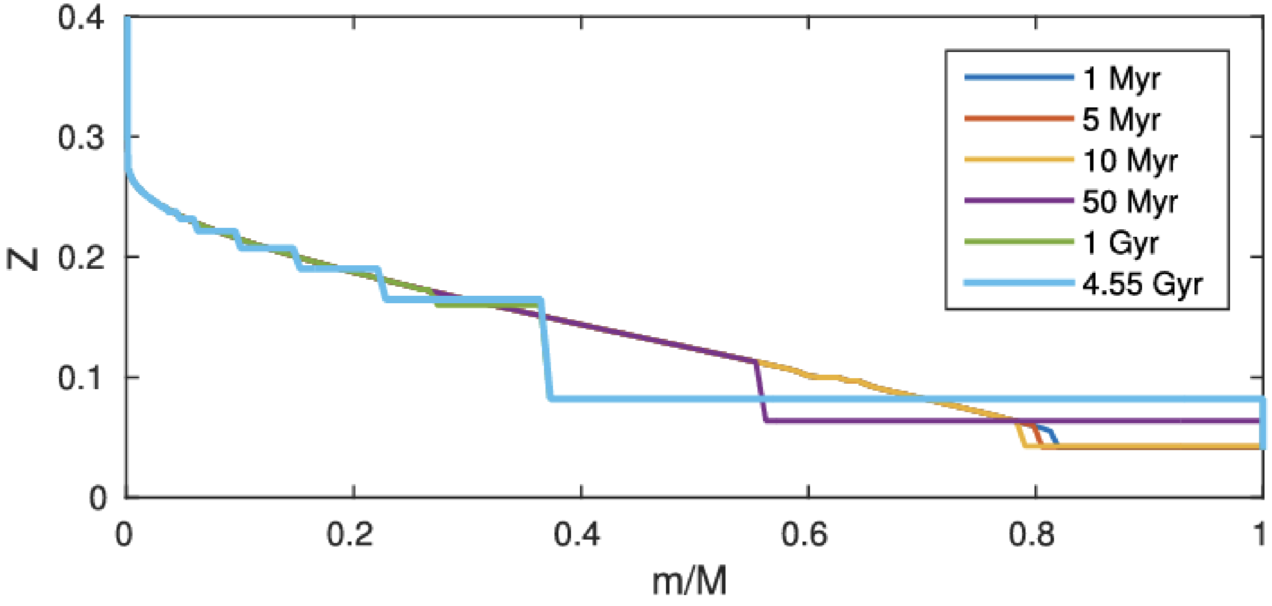

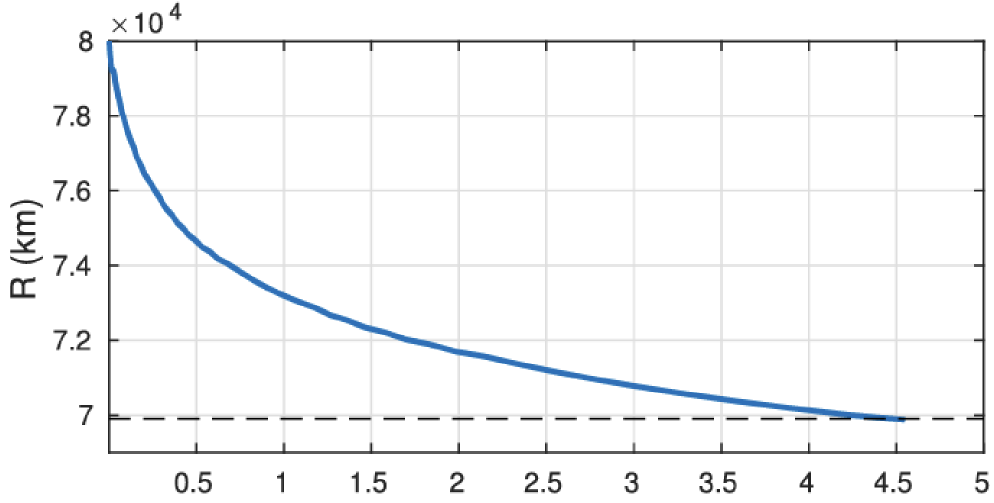

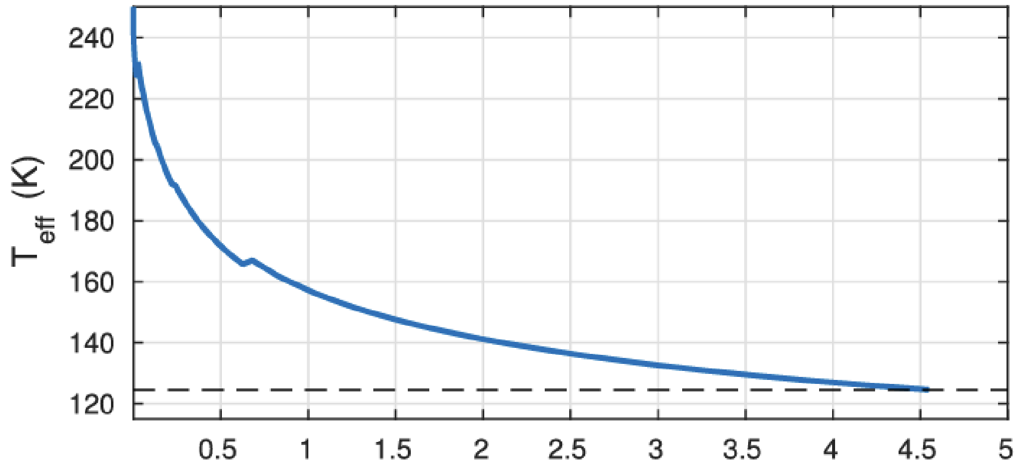

Problem: No Helium Rain

Old Evolutionary Models

- Homogenous and Adiabatic
- Non-homogenous (helium rain) and Adiabatic
- Non-homogeneous (extended cores), non-Adiabatic, but no helium rain
- Old Equations of State (EOS)
- Old Atmospheric boundaries

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New Evolutionary Models

- Non-homogenous: Constraints from Juno, and Cassini (fuzzy cores, Brunt), and helium rain,
- Heat Transport: Non-adiabatic (convection, radiation, and semi-convection)
- New H-He and heavy element EOSes
- New atmospheric boundary conditions

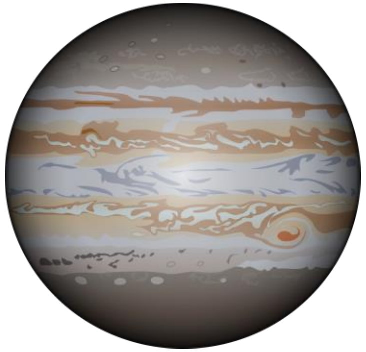
APPLE

A Next Generation Evolutionary Code for Modeling giant Planets

Sur, Su, Arevalo, Chen, Burrows

The Astrophysical Journal,
971:104 (19pp), 2024 August 10

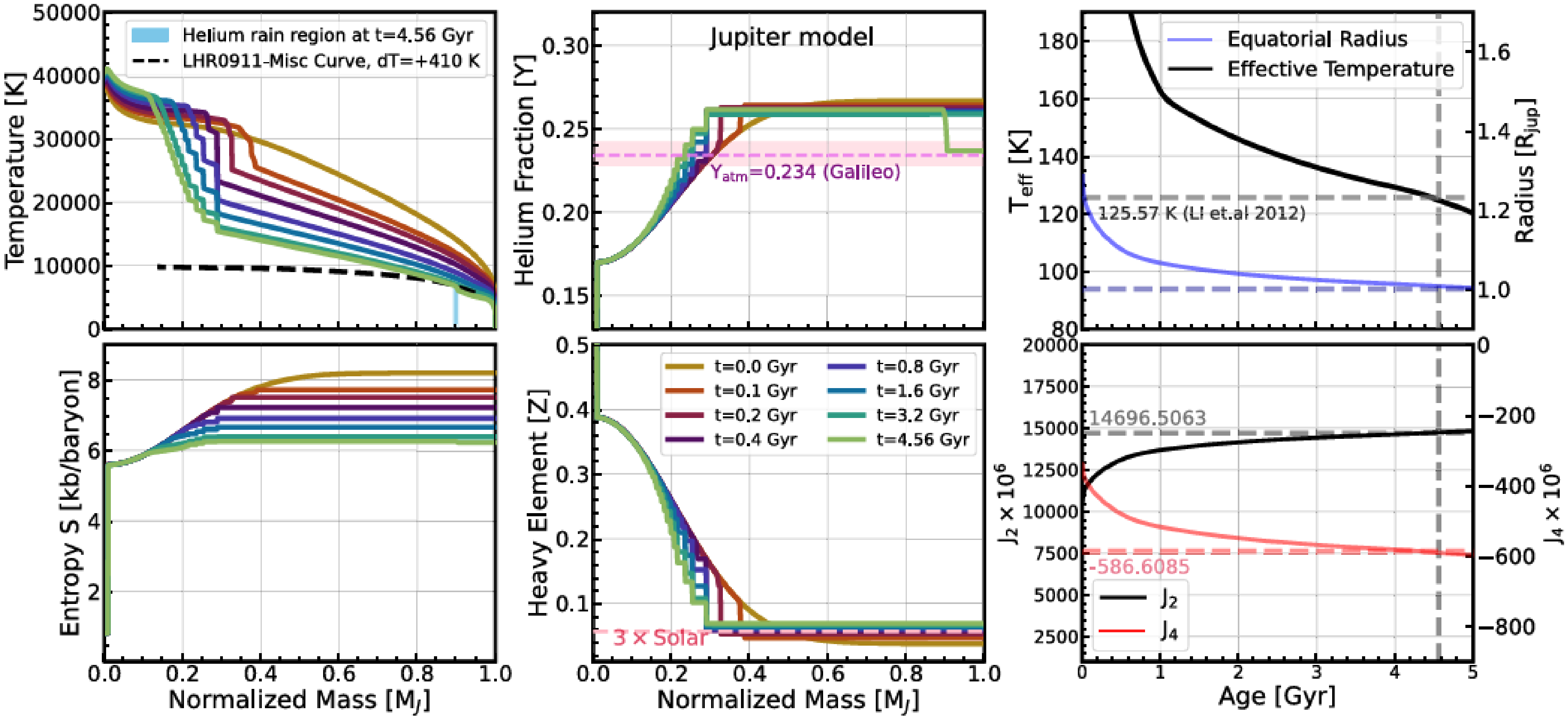
New Evolutionary Models for Jupiter and Saturn



Quantity	Jupiter	
	Measured	Our Model (4.56 Gyr)
$T_{\rm eff}$ (K)	125.57 ± 0.07 (1)	124.6
Equatorial Radius (km)	71492 ± 4 (3)	72019.5
Atmospheric Helium Fraction ($Y_{\rm atm}$)	0.234 ± 0.005 (4)	0.236
Atmospheric Metallicity ($Z/Z_{\odot}$)	1.5–5 (6)	3.6
$J_2 \times 10^{-6}$	14696.572 (7)	14731.6
$J_4 \times 10^{-6}$	−586.609 (7)	−591.46

Sur et.al ApJ 2025

Total heavy element mass
~ 42 Mearth (13%)



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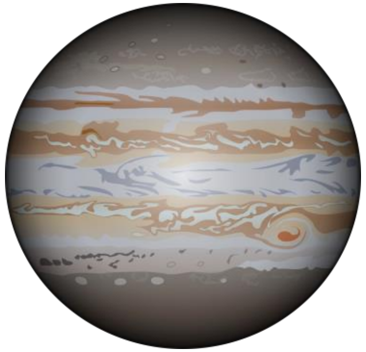

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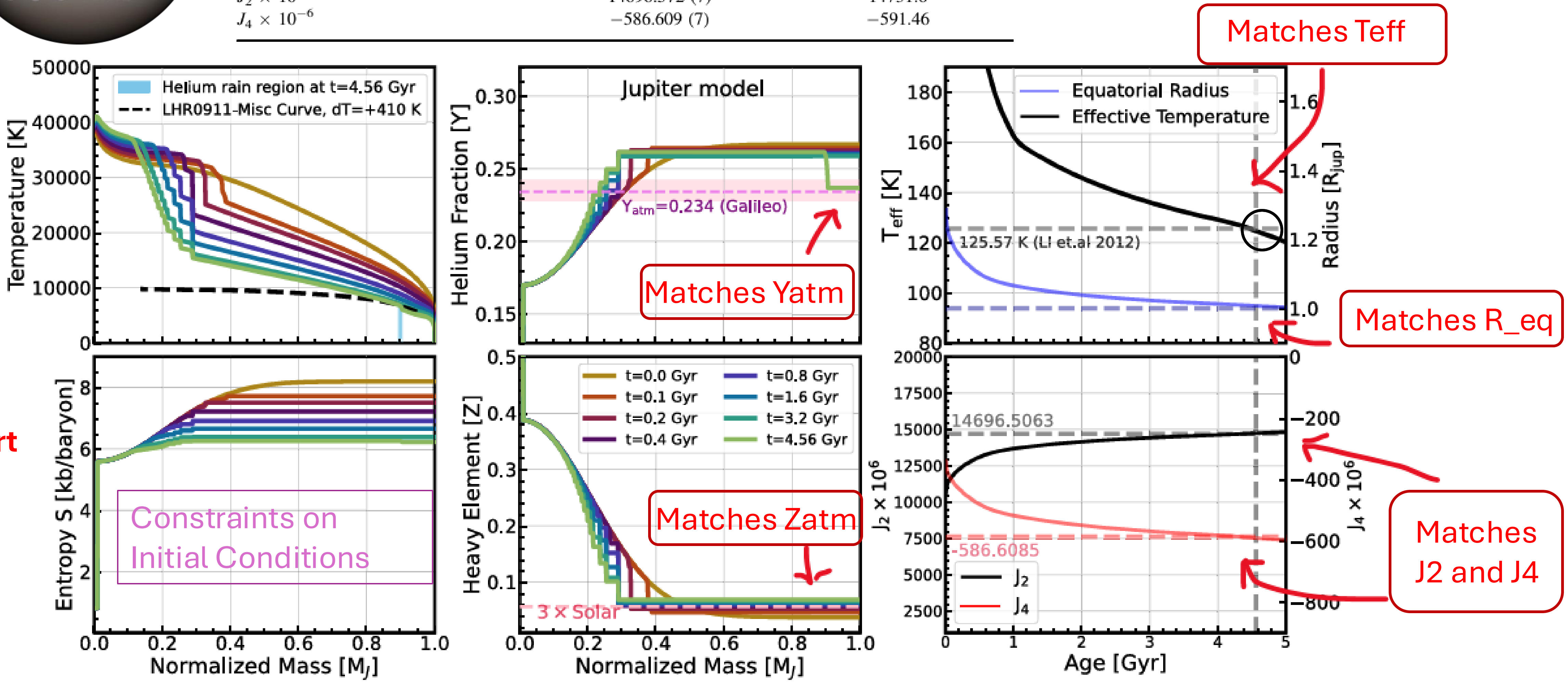
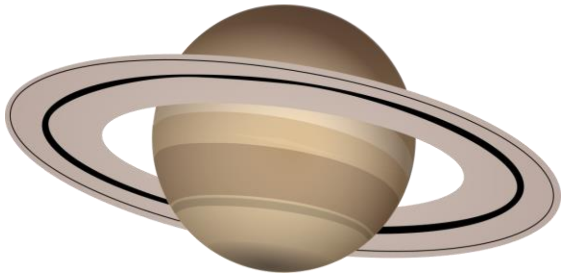
Cold-Start



New Evolutionary Models for Jupiter and Saturn

Sur et.al ApJ 2025



Quantity	Saturn	
	Measured	Our Model (4.56 Gyr)
$T_{\rm eff}$ (K)	96.67 (2)	96.54
Equatorial Radius (km)	60268 ± 4 (3)	59,551.8
Atmospheric Helium Fraction ($Y_{\rm atm}$)	0.075–0.22 (5)	0.205
Atmospheric Metallicity ($Z/Z_{\odot}$)	5.0–10.0 (6)	4.6
$J_2 \times 10^{-6}$	16290.573 (8)	16365.7
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Total heavy element mass
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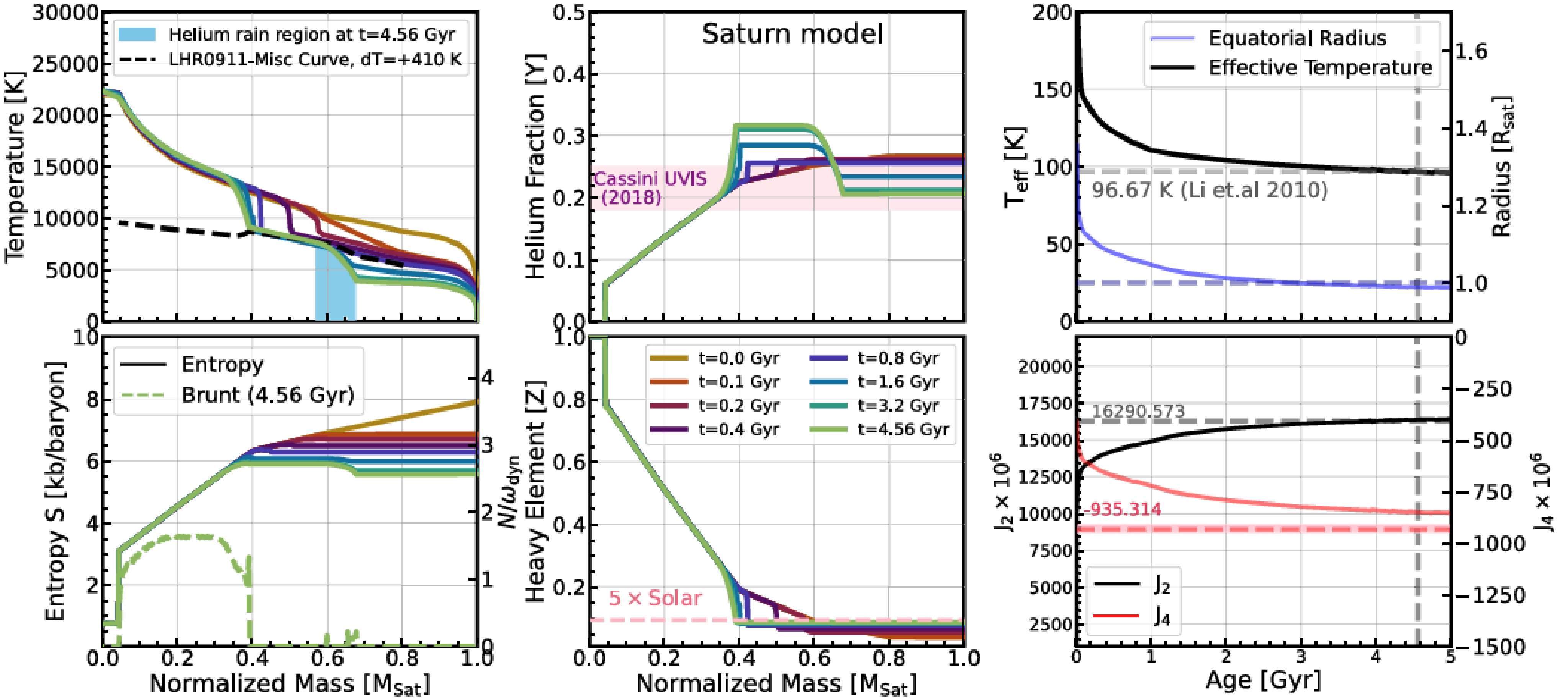

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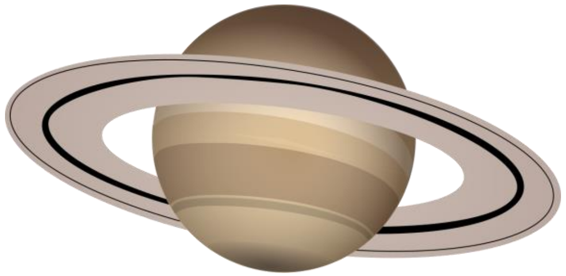

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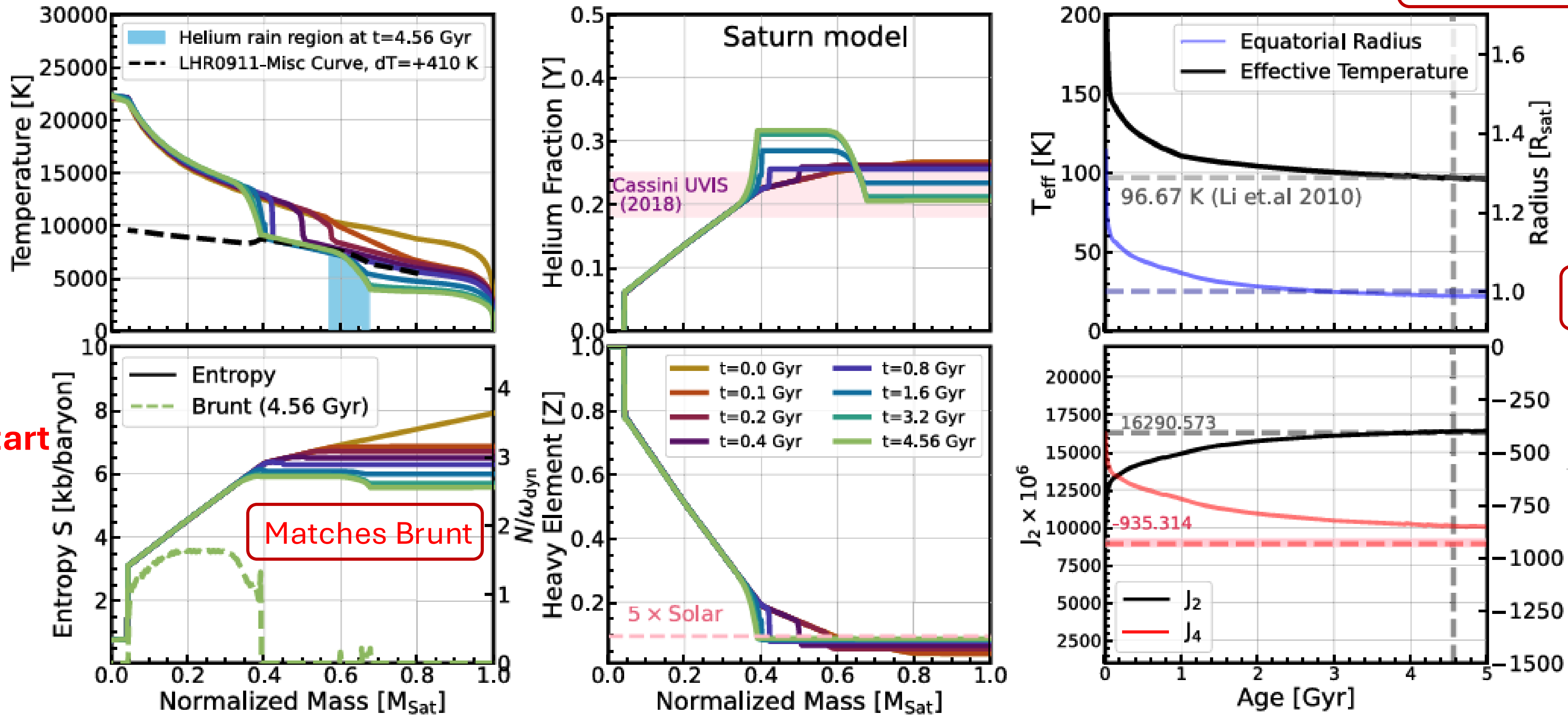


Matches Teff

Matches R_eq

Cold-Start

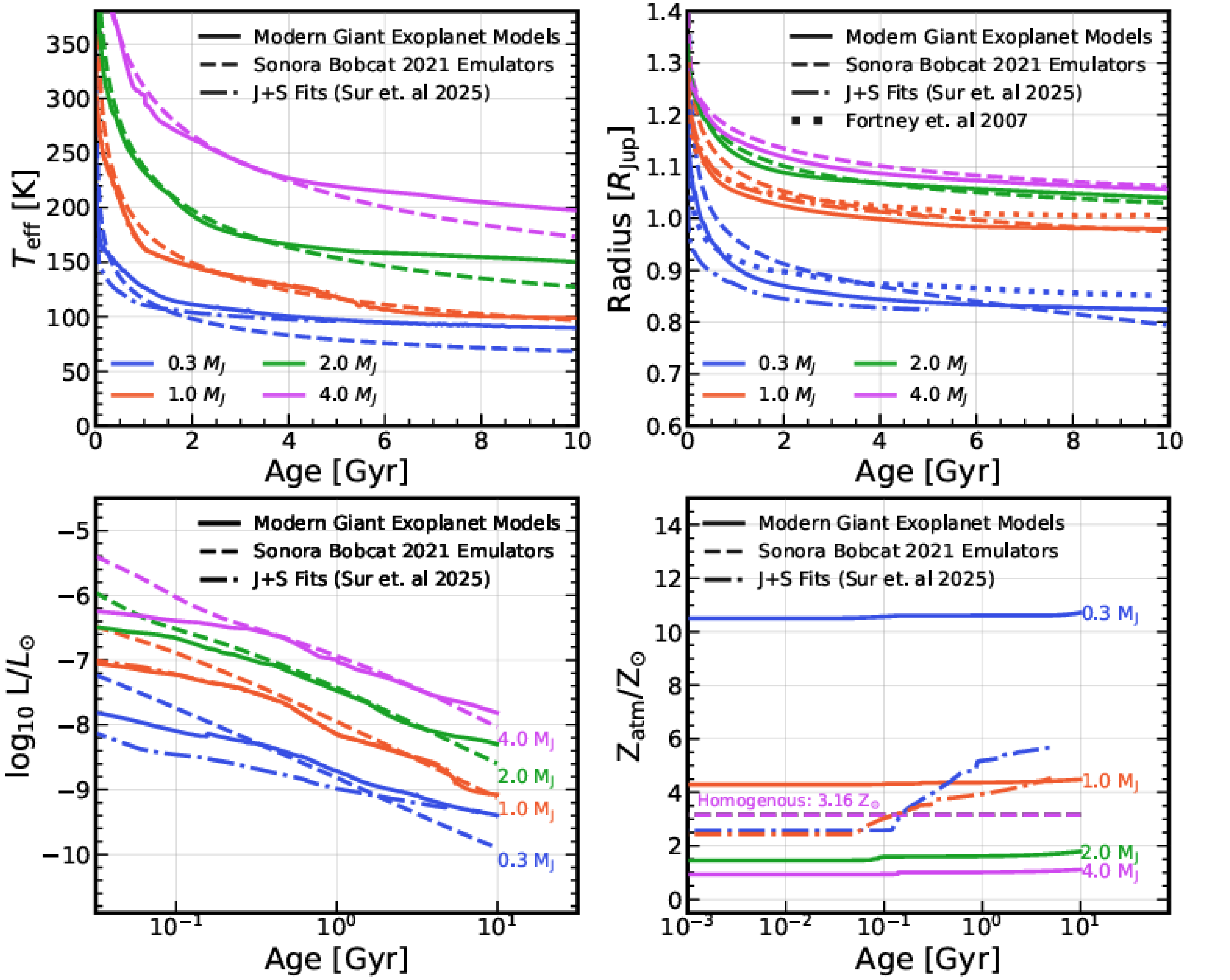
Matches Brunt

Matches J2

Not J4

New Evolutionary Models for Giant Exoplanets

Sur et.al (under review ApJ, 2025)



Comparing with Sonora Bobcat Models

Improvements:

- Use real heavy element EOS
- Helium rain
- Non-adiabatic evolution
- Fuzzy cores

Results

- Predictions for Zatm
- Teff higher by 10-20%
- Radii differ by 5-10%

Conclusions and Summary

- Non-adiabatic models are required.
- Need improved EOSes and miscibility diagrams.
- Fuzzy cores vs Homogeneous.
- Cold-start initial conditions
- Saturn's Yatm~0.2