Convective mixing in hot Jupiters

How do atmospheric abundances and bulk composition relate?

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Context

It has long been assumed that giant planets consist of a well-defined core consisting of mainly heavy elements and a convective homogeneous envelope consisting mainly of H/He. Measurements by the Juno and Cassini missions suggest that the chemical structures of Jupiter and Saturn respectively are more complex, with them possibly containing a dilute core. It is essential to understand how and when dilute cores form and evolve during a planet's evolution, to be able to relate atmospheric properties to bulk compositions and to link this to the planet's history using planet formation models. These efforts have only become more important now that high quality transmission spectra using JWST are coming in. These provide us with great insight into the atmospheric composition of exoplanets.

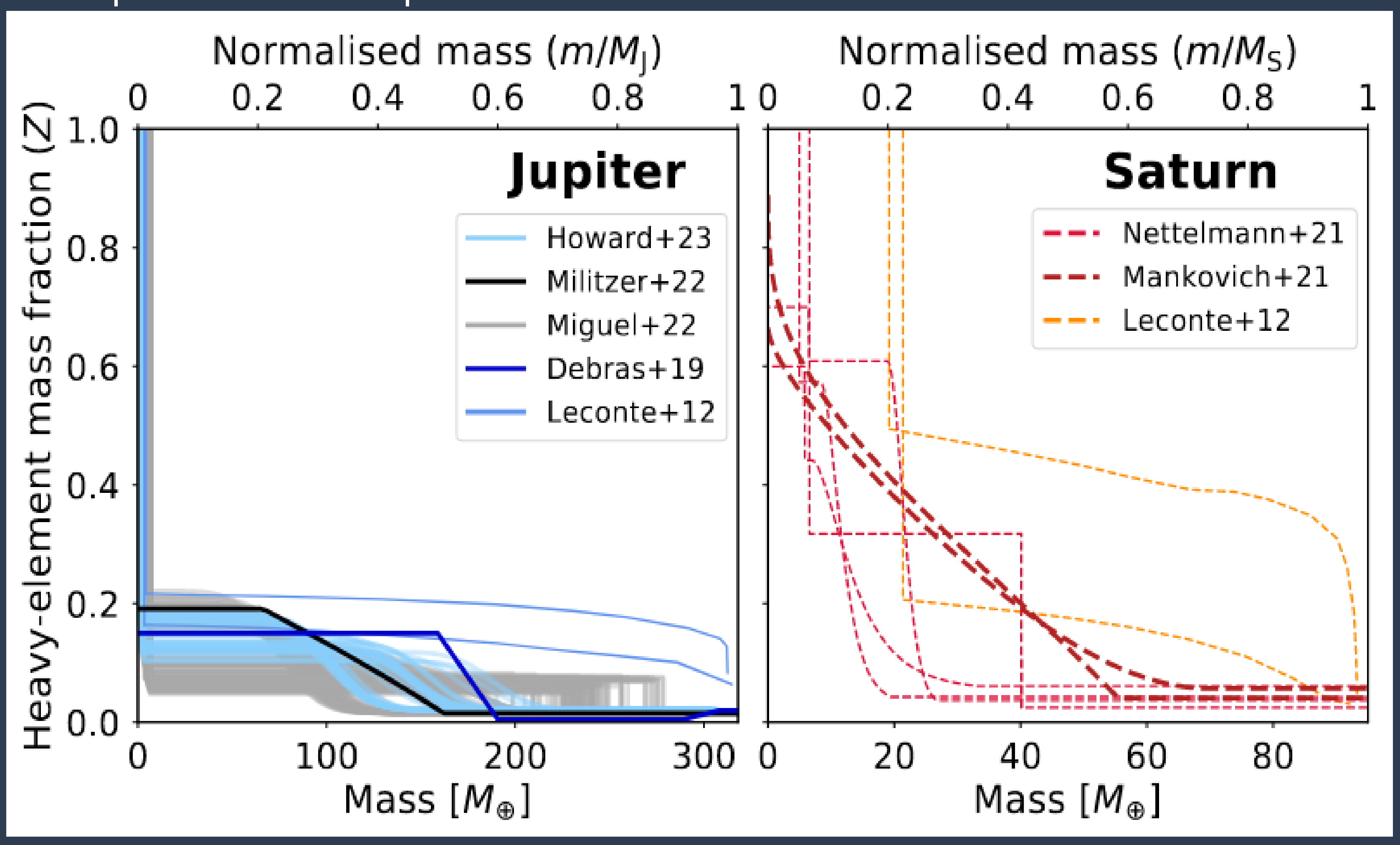

Fig. 1: The distribution of heavy-elements (Z) suggested by different models for Jupiter and Saturn internal structure.(1)

Method

We use the planetary evolution model *Completo21*(2) as the framework for our study. We have updated the structure equations to include convective mixing according to the Ledoux criterion and have added a better internal luminosity distribution, including an expression for the additional internal heating term due to bloating. In our analysis we use a Jupiter-like planet as a test case using chemical structures that were used in previous studies either based on formation models(3) or made to match present-day observational properties.(4) We then look at what we expect for hot Jupiters.

Table 1: The standard parameters used in our model. α is the mixing length parameter. Semi-convection is not included in our standard case, but can be added via the parameter α_{sc}. The parameter n_{mesh} determines the size of the mesh in our model.

L_{init}	$10^3\ L_J$
M_{core}	$1\ M_E$
$M_{envelope}$	$316.83\ M_E$
Y	0.274
α	10^{-3}
α_{sc}	0
n_{mesh}	5×10^4
Orbital distance	5.2, 0.03 AU
$M_\star$	$1\ M_\odot$

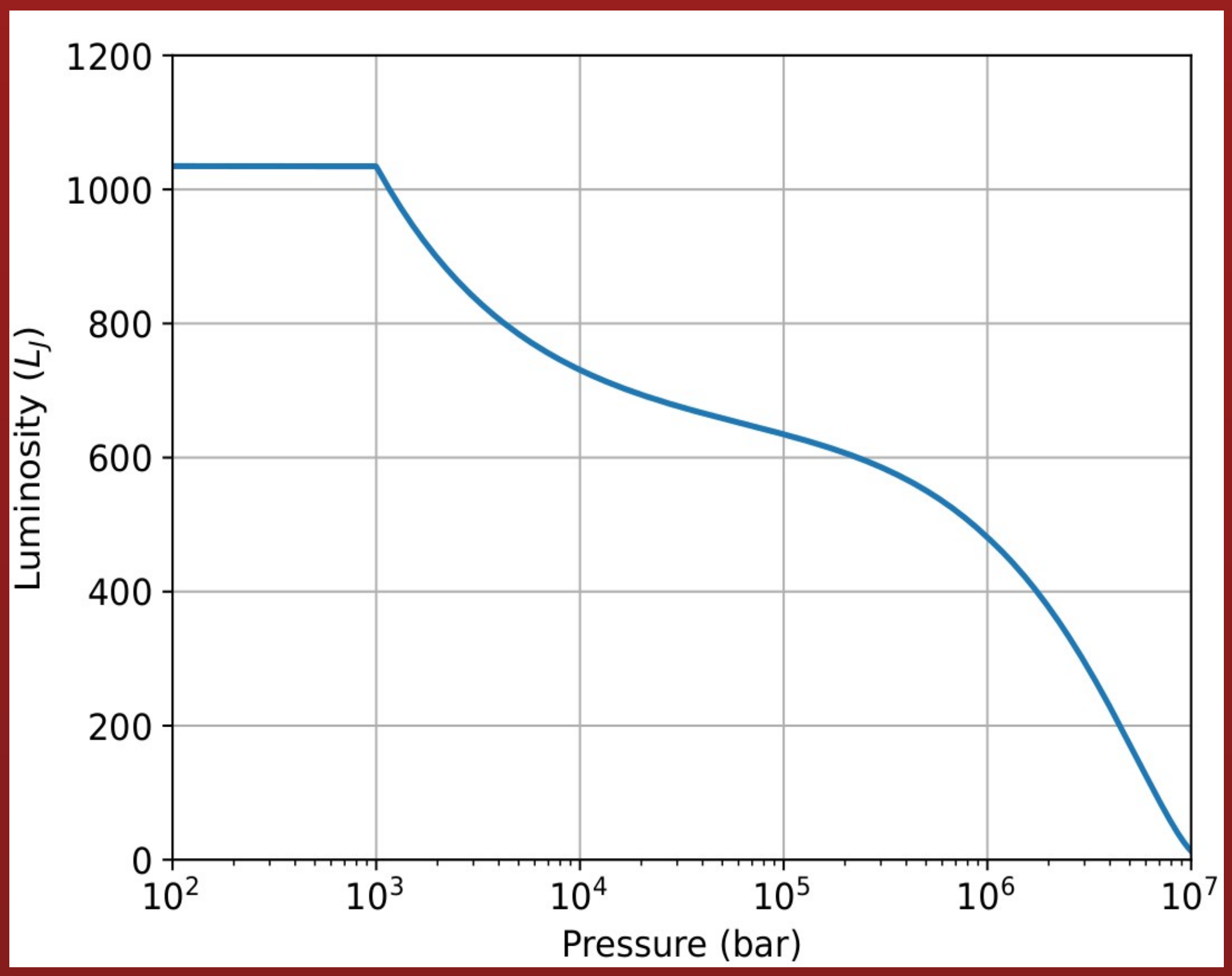

Fig. 2: The internal luminosity as a function of the pressure for a hot Jupiter at 0.03 AU. The internal luminosity scales linearly with the mass, while the bloating luminosity is added between 10^3 and 10^6 bar.

Results

Dilute cores can be retained for several different initial heavy-element distributions. The effect of convective mixing and the formation of dilute cores only have a small effect on the present-day luminosities and radii of the planets compared to a fully-mixed model. We find that the effect of bloating is small, limiting convection minimally by decreasing the luminosity near the core during the early stages of evolution.

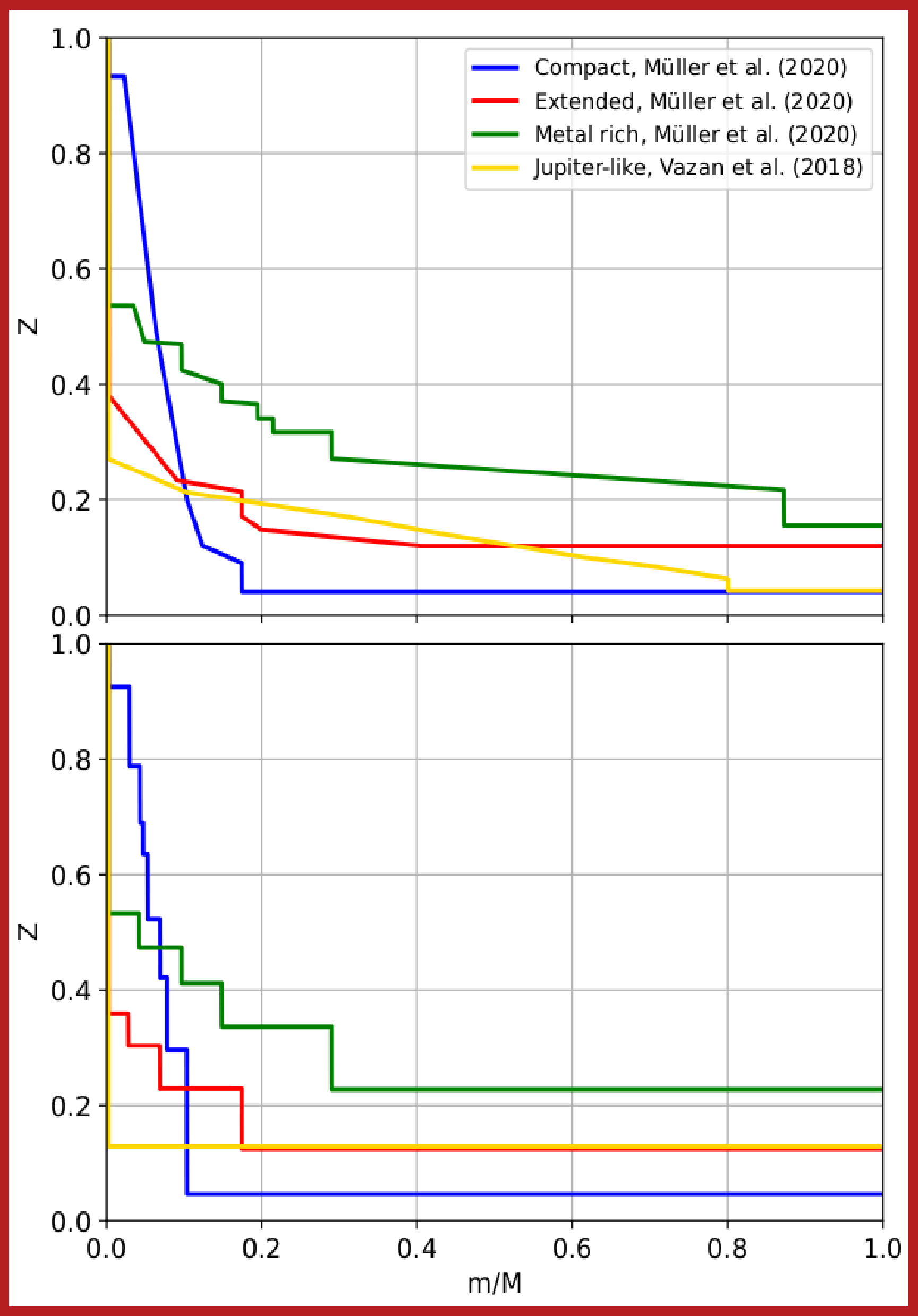

Fig. 3: The initial and final heavy-element distribution for our standard case. We find that most chemical structures are able to retain a dilute core. This is not the case for the Jupiter-like structure, due to the compositional gradient being too small to inhibit convection. Dilute cores extend to between 10 and 30% of the mass.

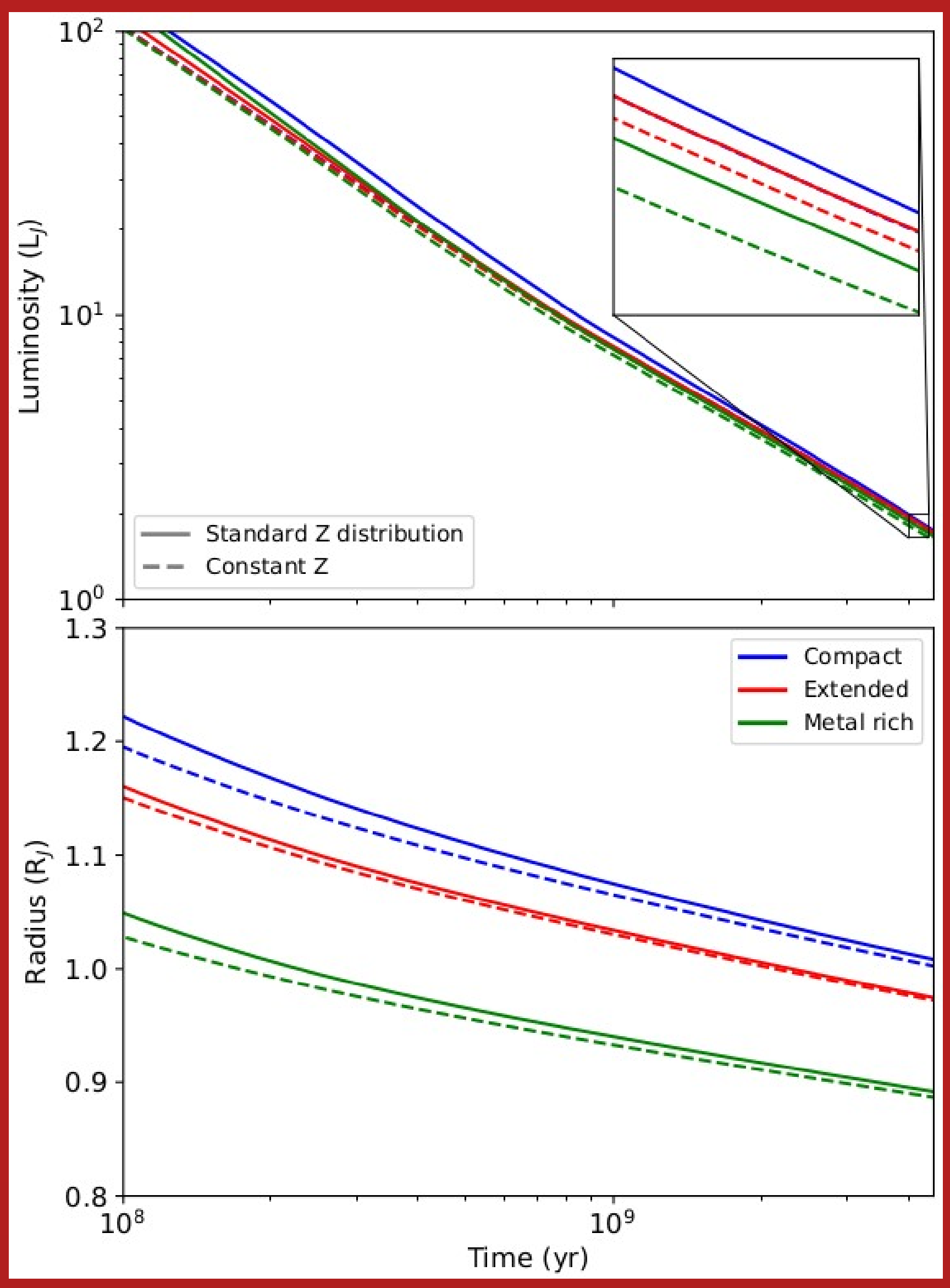

Fig. 4: The luminosity and radius as a function of time comparing fully mixed envelopes with our current models. We find differences in the luminosities and radii early on, with the luminosity increasing early on due to the mixing process. The differences become smaller as the planets continue to evolve.

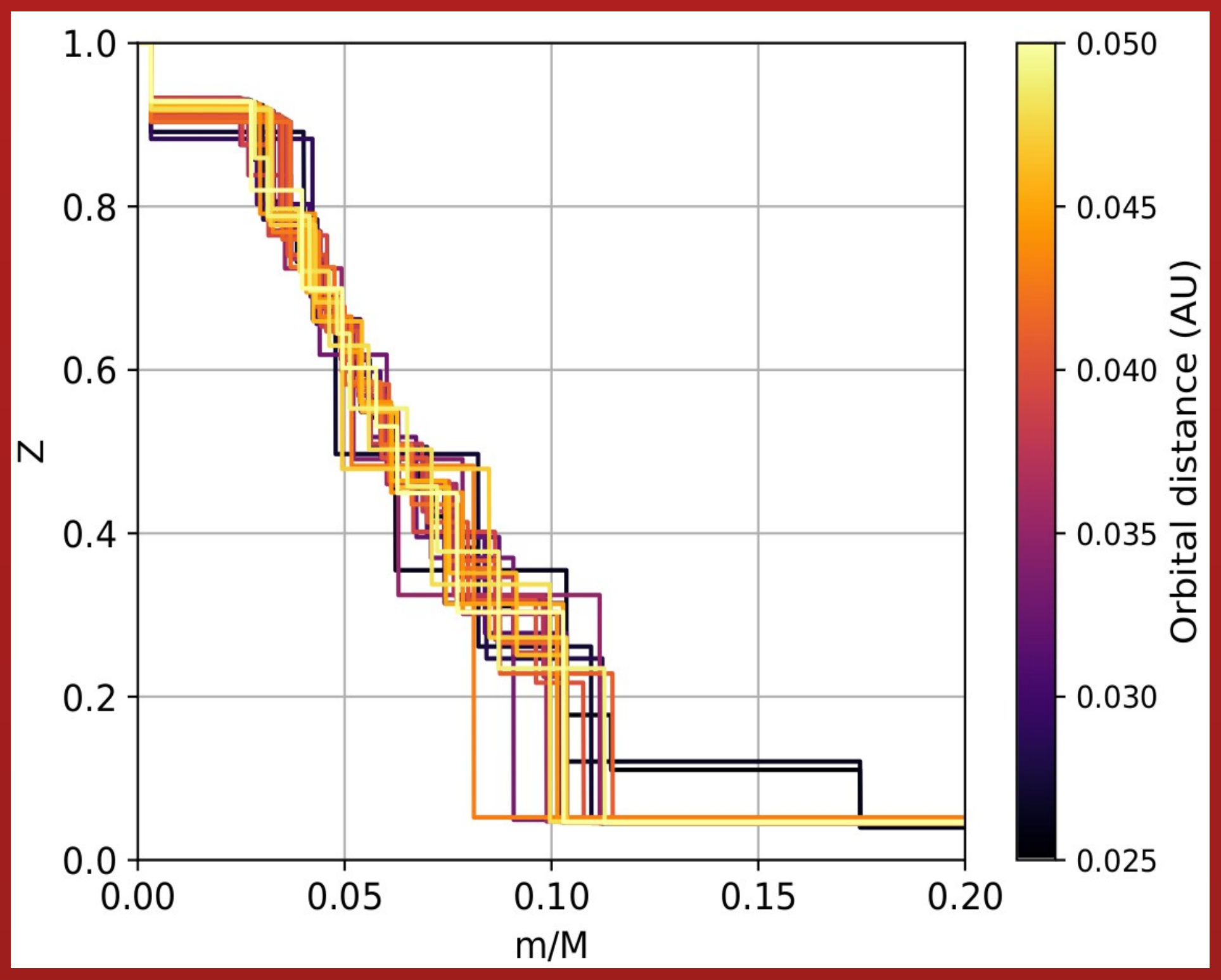

Fig. 5: The final heavy-element fraction for the compact initial structure for a hot Jupiter at different orbital distances. Closer-in planets have a stronger bloating luminosity, while the other internal luminosity term becomes smaller. We find a weak relation with the orbital distance, with strongly irradiated planets retaining a slightly larger dilute core.

Conclusion

-We find that dilute cores can be retained for $L_{init} \leq 3 \cdot 10^3\ L_J$
-Semi-convection can impact the final structure, but is not capable of fully mixing dilute cores
-The impact of bloating is small in all but the most extreme cases

We conclude that it is unlikely that a large fraction of hot Jupiters has dilute cores left over from formation, due to the necessity of low initial luminosities.

References

(1)-Helled, R. & Stevenson, D.J. 2024, AGU adv. 5, 2 (2)-Mordasini, C.M. et al. 2012, A&A 547, A111 (3)-Müller, S. et al. 2020, A&A 638, A121 (4)-Vazan, A. et al. 2018, A&A 610, L14

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