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**THERMAL EVOLUTION OF URANUS AND NEPTUNE WITH
CONDENSATION-INHIBITED CONVECTION**

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requirements for the degree of

BACHELOR OF SCIENCE

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ASTROPHYSICS

by

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Introduction

Giant planets radiate away their latent heat of formation through the top of their atmosphere. If they cool to a point where the amount they radiate away is equal to the amount of radiation they receive from their parent star, they enter thermal equilibrium with their surroundings. At the present time, the giant planets in our solar system: Saturn, Jupiter, Uranus, and Neptune, all have effective temperatures greater than their equilibrium temperature, except for Uranus. Observations of Uranus show a planet that appears to be in thermal equilibrium with its parent star, a 'dead' planet with no intrinsic temperature, cooler than its more distant neighbor, Neptune. Thermal evolution models for Uranus have not matched observation, instead predicting a warmer effective temperature at 4.6 Gyr, the current age of the solar system. (Fortney et al., 2011), (M. Podolak, 1991), (W.B. Hubbard, 1995), (L. Scheibe, 2019) [There are other papers by Nettelmann 2013, Linder 2019 that I haven't looked at yet].

There have been various attempts to explain the cool Uranus. Early investigations posited a stratified interior, possibly stable against convection, that would allow heat

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Model

2.1 Baseline Structure with Dry Convection

The physics of the interior structure of the solar system gas and ice giants, and attempts to model their thermal evolution, date back to the mid to late twentieth century, with the first observation of Jupiter’s intrinsic temperature by Low (1966), with subsequent investigations into the theory of giant planet structure and evolution (Hubbard, 1977b), (Hubbard, 1977a), (M. Podolak, 1991). We begin with a description of the physics of our baseline structure model, starting with the conservation of mass:

$$\frac{dm}{dr} = 4\pi r^2 \rho \tag{2.1}$$

where dm is the mass contained within a sphere of radius r , and $\rho(r)$ is the density at radius r . Hydrostatic equilibrium is also assumed and described by:

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2} \tag{2.2}$$

The temperature-pressure profile follows a dry adiabat gradient(R. Kippenhahn, 2012), given by :

$$\nabla_{\text{ad}} = \left(\frac{\partial \ln T}{\partial \ln P} \right)_s \quad (2.6)$$

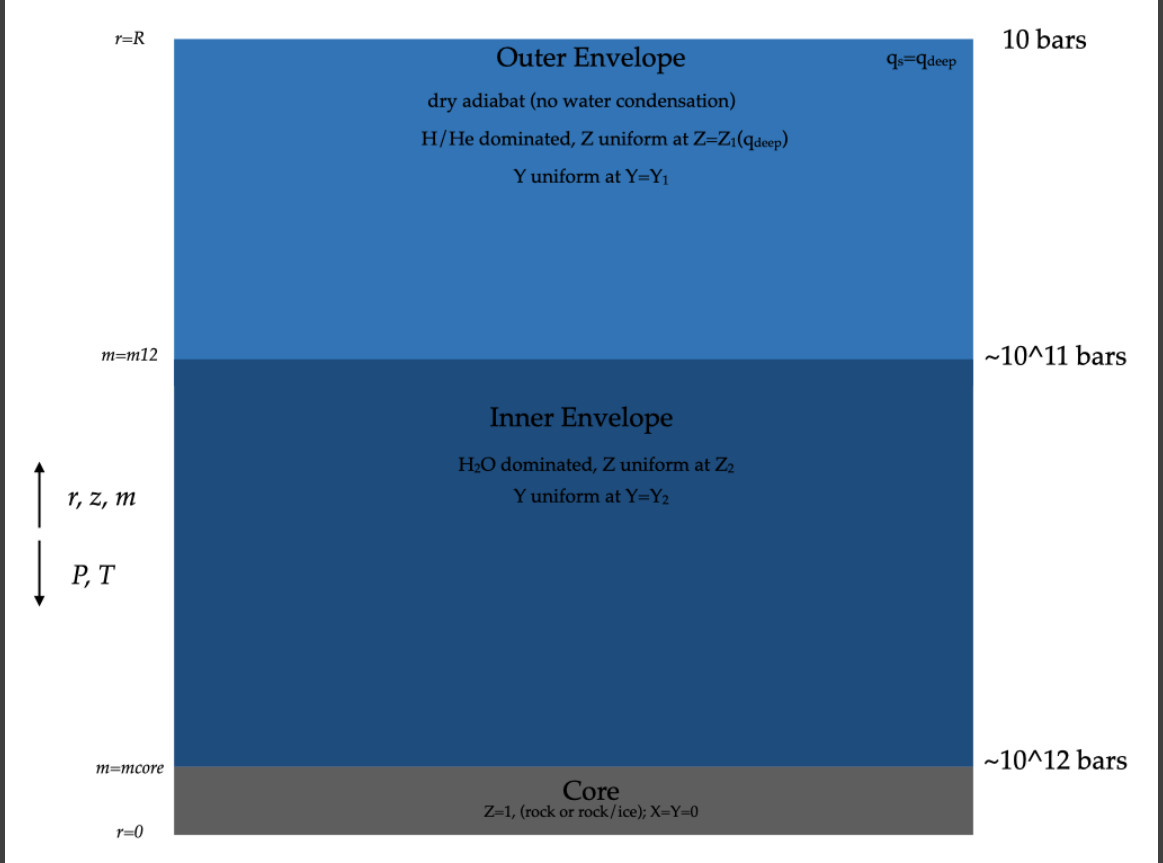


Figure 2.1: The structure for a fully convective, dry adiabatic interior. In this model, the inner and outer envelopes are assumed to be well mixed, fully convective, and following a dry adiabat. The core is composed of rock and ice. The inner envelope is water dominated, with uniform concentrations of hydrogen, helium, and water; whereas, the outer envelope is hydrogen and helium dominated, with trace amounts of water. The 'atmosphere' exists above 10 bars.

Finally, beyond the outer envelope is the atmosphere. When modeling the ther-

mal evolution of gas and ice giants, it has long been recognized that model atmospheres constitute an outer boundary condition for interior structure models, providing key inputs that impact cooling times for interior structure models. Our work considers both (Harold C. Graboske & Olness, 1975) and (Fortney et al., 2011) model atmospheres. Unless otherwise stated, our results will utilize the Fortney 2011 model atmospheres.

2.2 Inclusion of Moist Convection Within Outer Envelope

Our interior structure model departs from the standard model described above by adding a moist adiabatic layer to the outer envelope that, under favorable conditions, allows for the condensation of H_2O . Gases condense at sufficiently low temperatures or high pressures (cite pierrehumbert). Condensation of a gas is characterized by its saturation vapor pressure, P_{sat} , given by:

$$P_{\text{sat}}(T) = P_{\text{sat}}(T_0)e^{-\frac{1}{R_{\text{gas}}}\left(\frac{1}{T}-\frac{1}{T_0}\right)} \quad (2.7)$$

where R_{gas} is the gas constant for the condensible species. When the partial pressure of a gas, P_{gas} , is less than P_{sat} , the parcel of gas is 'unsaturated'. When $P_{\text{gas}} = P_{\text{sat}}$, the gas is 'saturated'. And, when $P_{\text{gas}} > P_{\text{sat}}$, the parcel is 'supersaturated'. Each condensible species has its own saturation vapor pressure.

The condensation of water in the interior of hydrogen-dominated atmospheres has some notable differences with our experience of water condensation within our own planet's atmosphere (Leconte et al., 2017) (Friedson & Gonzales, 2017) (Guillot, 2019) (Guillot, 1995). On Earth, H_2O lighter than the background air, which is composed primarily of N_2 . So, while condensation of water in the interior of ice giants does release heat through

the latent heat of condensation, which in the presence of a heavier background gas would result in an instability, the situation is different when the background is hydrogen-helium dominated. In this case, a strong vertical gradient in mean molecular weight arises, creating a negative buoyancy. This may result in the formation of a layer that is stable against convection (citations).

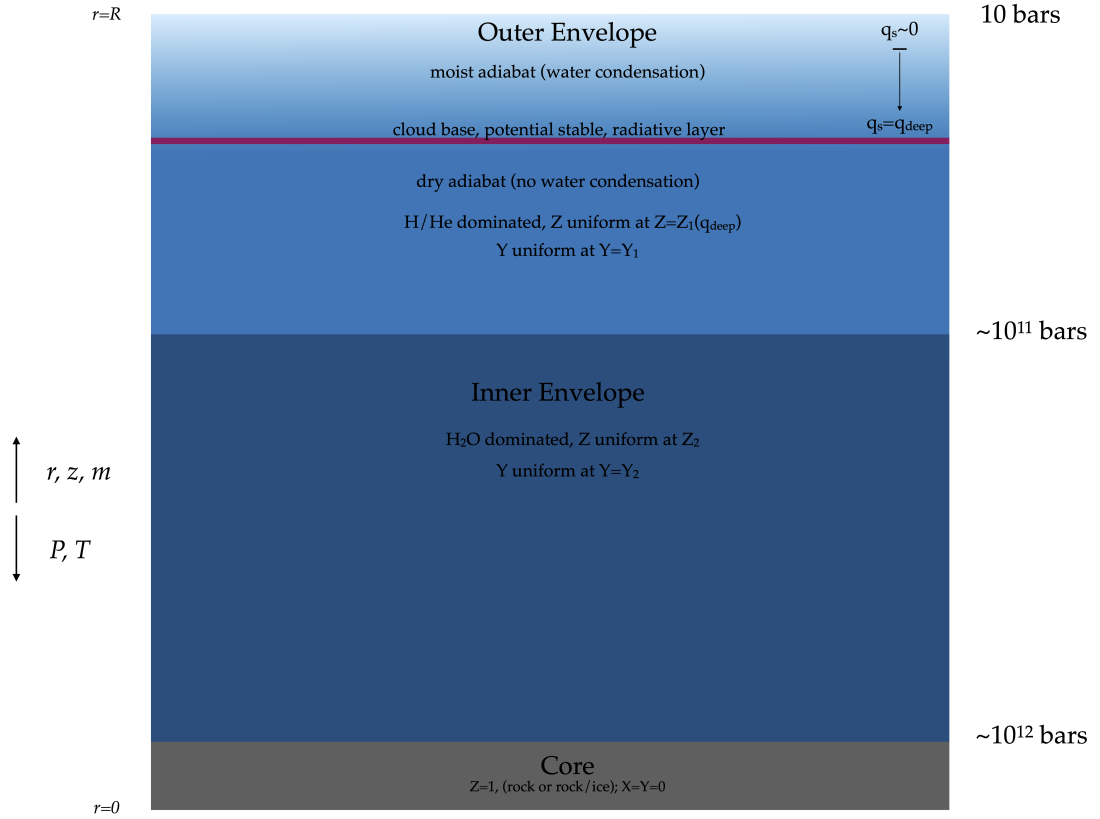


Figure 2.2: The structure for moist adiabatic interior, allowing for condensation-inhibited convection.

If condensation zone forms, it may be stable against convection. Convection is inhibited due to the formation of a stable condensation zone when $\alpha < 1$, where α (Friedson & Gonzales, 2017) is given by:

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Results

3.1 Condensation-inhibited Convection

Talk about Figure 3.1.

3.2 Formation of Radiative Layer

Talk about Figure 3.2.

3.3 Thermal Evolution

Talk about Figure 3.3.

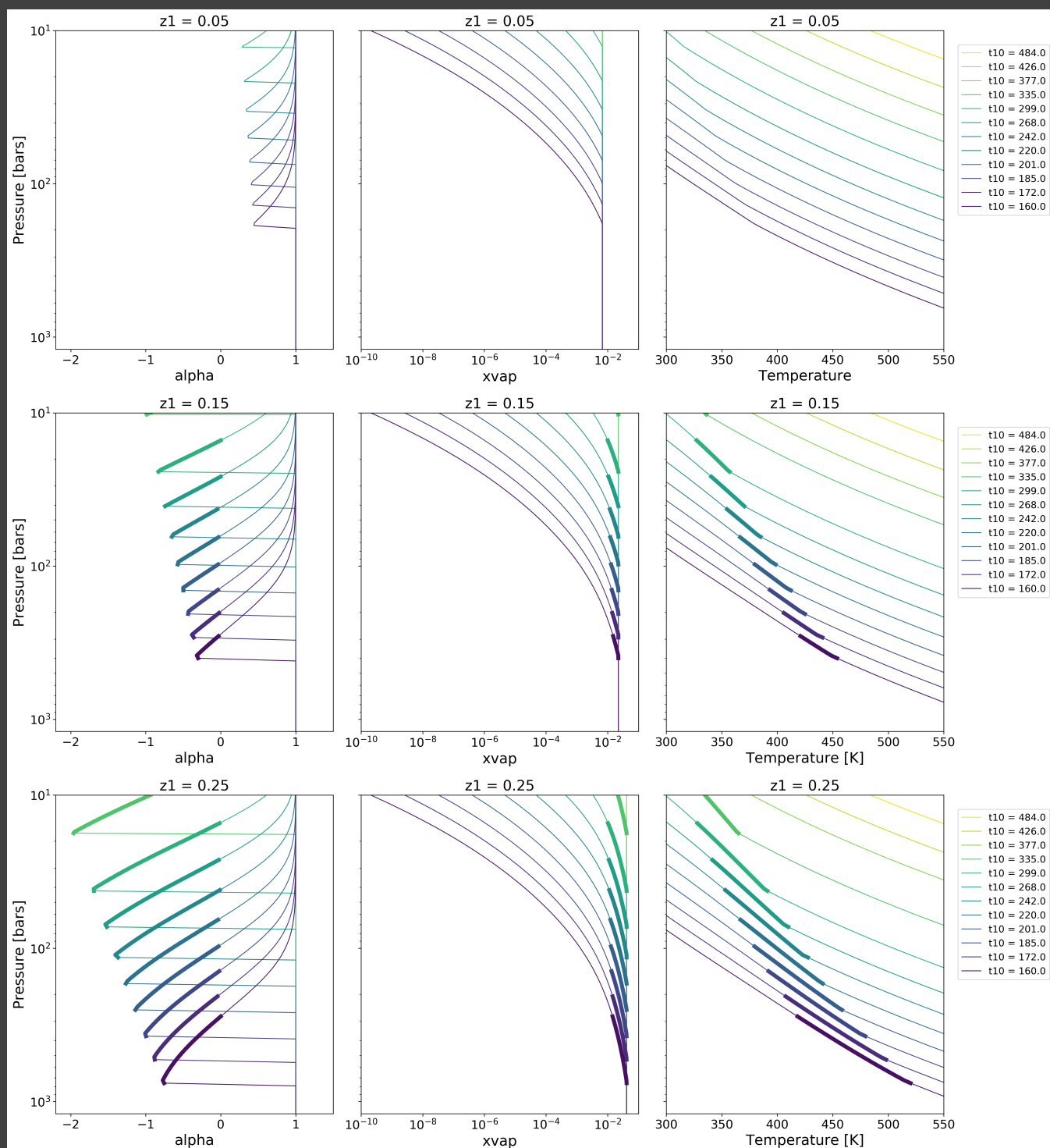


Figure 3.1: add description re: moist adiabat, when/where convection is inhibited and where the radiative zone base is in these plots. explain differences

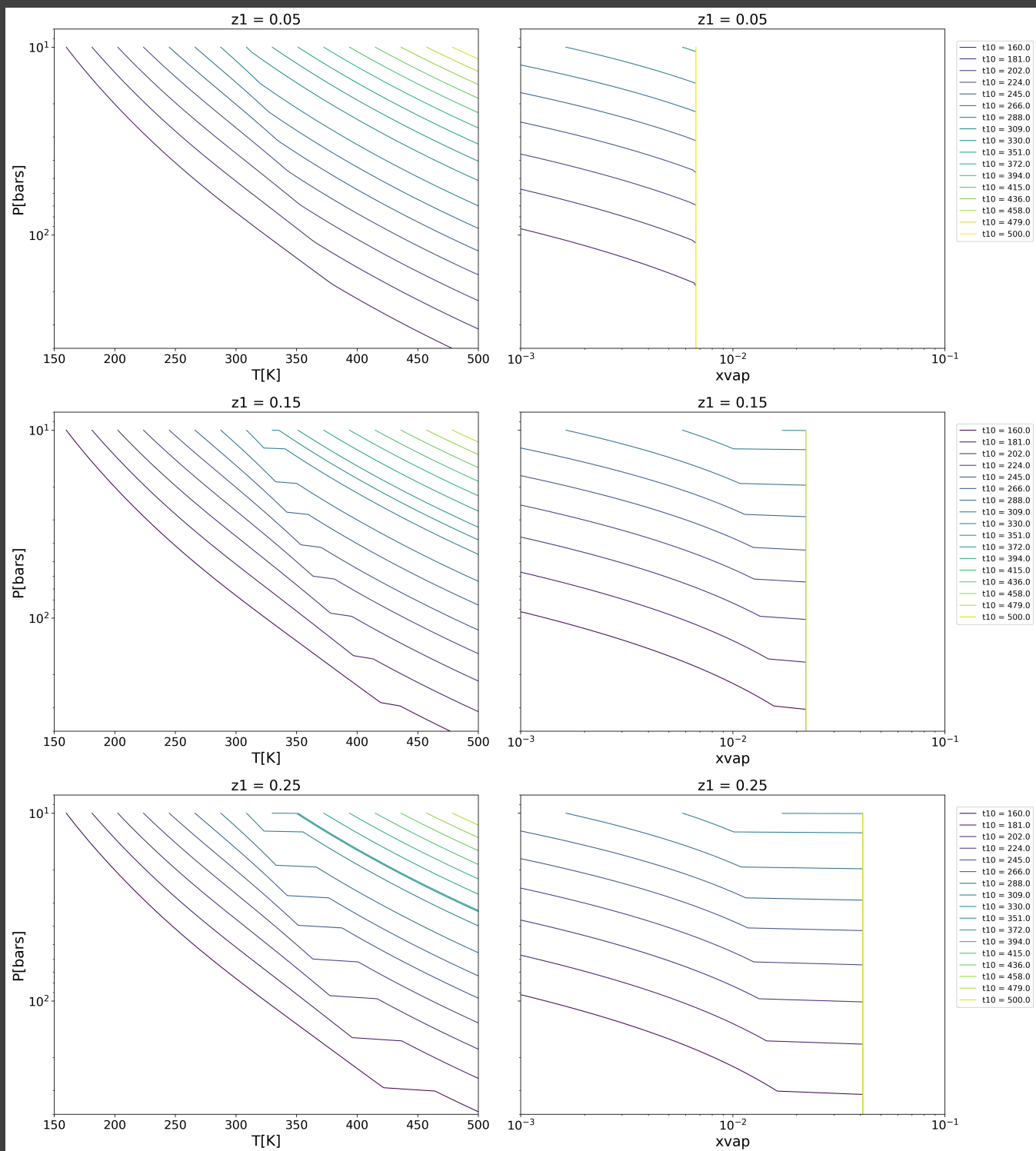


Figure 3.2: add description these plots. explain differences

4

Discussion and Conclusions

Appendix A

Some Ancillary Stuff

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