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Giant Planet Evolution: The Effect of Convection and Mixing

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Abstract

We model the long-term evolution of giant planets accounting for the change in the compositional gradient with time. Core erosion is modeled by convective-mixing using both the Ledoux and Schwarzschild criteria for convection. We find that in some cases compositional gradients prevent convective mixing, and as a result, the assumption of an adiabatic interior is no longer valid. In other cases, mixing leads to layered-convection, which results in a stair-like internal structure and a slower cooling [2]. In addition, the process of mixing (if it occurs) enriches the gaseous envelope in heavy elements from the core. These have a direct effect on the planetary evolution, and therefore on the planetary radius and luminosity. We suggest that the memory of the primordial internal structure remains even after billions of years.

1. Introduction

The existence of heavy-element cores in gas giant planets and their physical properties are important for understanding giant planet formation, evolution, and internal structure. Typically, evolution models assume a compositional distribution that does not change with time. This assumption, however, is not necessarily correct. It is possible that the heavy-element core becomes soluble in the gaseous envelope [4]. Recent studies of the solubility of analogous phases have shown that heavy elements can dissolve in liquid metallic hydrogen in planetary interior conditions (e.g. [6]).

2. Convection

We use a planetary evolution code [1,5] that models convection by using the Ledoux criterion:

$$\nabla_R > \nabla_A + \nabla_{Ledoux} \tag{1}$$

where ∇_A and ∇_R are the adiabatic and radiative gradients, respectively. The compositional gradient of material X of type j contributes the convection via

$$\nabla_{Ledoux} = \sum_j \frac{\partial \ln T}{\partial X_j} \frac{\partial X_j}{\partial \ln p} . \tag{2}$$

For $\nabla_{Ledoux} = 0$ the Ledoux convection criterion converges to the Schwarzschild criterion.

When mixing of materials is considered, we use the compositional balance equation allowing for convective-mixing-diffusion by:

$$\frac{\partial X_j}{\partial t} = -\frac{\partial F_j}{\partial m} . \tag{3}$$

The particle flux of the j^{th} species F_j is proportional to the abundance gradient, and is determined by the Mixing Length Recipe (MLR) [3,1].

3. Results

During the planetary evolution, a "competition" between the stabilizing effect of the compositional gradient and the un-stabilizing effect of the temperature gradient essentially determines the planetary evolution and the final structure of planet. For example, when using the Ledoux criterion for an initial configuration of core + envelope, convection cannot occur in the core-envelope boundary which acts as a ”bottle neck” for the heat transfer. This leads to a much warmer interior and a slower cooling rate. On the other hand, an initial structure with a gradual distribution of the heavy elements can evolve into an interior with layered-convection, where several convective regions in the planet are separated by thin diffusive layers, i.e., a stair-like internal structure. The cooling rate of the planet is controlled by this structure, which affects also the heavy element enrichment of the envelope.

Figure 1 presents the heavy element distribution after 10^{10} years of evolution, for different initial configurations. For all cases the Ledoux criterion is used and mixing is simulated using MLR.

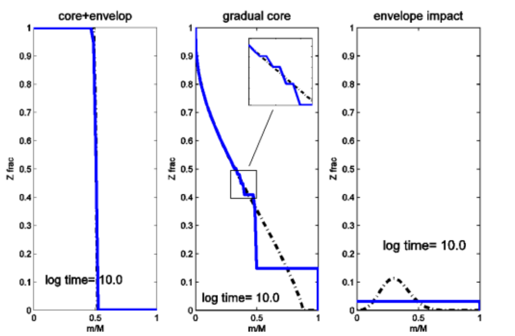

Figure 1: *Heavy element mass fraction vs. normalized planetary mass for 1 M_J planets with different initial distributions. Initial structure (dashed dotted) and a structure after 10^{10} years of evolution (solid) are presented.* ***Left:*** *pure heavy element core and gaseous envelope;* ***Center:*** *gradual distribution;* ***Right:*** *local heavy element "cloud".*

Figure 2 shows the effect of the mixing and convection criterion on the radius' evolution for a 1 M_J planet with a primordial gradual composition distribution (as in Fig.1 center).

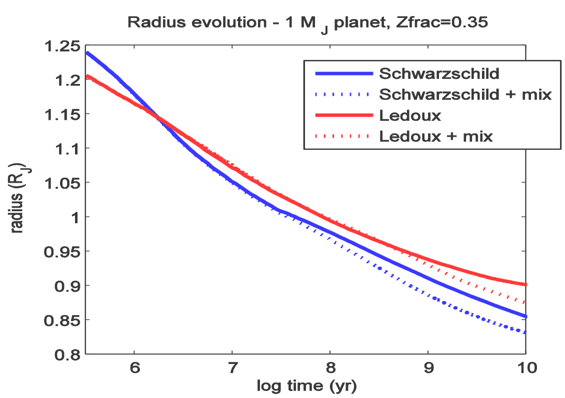

Figure 2: *Radius' evolution of 1 M_J planet with z=0.35 assuming a gradual initial distribution, for different convection criteria (blue – Schwarzschild, red – Ledoux), with (dotted) and without (solid) elements mixing.*

As expected, for the Ledoux criterion (red curves) convection regions are limited due to the stabilizing compositional gradient. This leads to a slower heat transfer rate and slower contraction, and therefore, a larger radius. When only the temperature gradient is considered (blue curves), the cooling is faster, leading to a smaller radius. When mixing is allowed (dotted curves) the heavy elements mix within the gaseous envelope leading to smaller radii after about 10^8 years. The planetary radius for a stair-like internal structure (red dotted) contracts in the same rate (or even faster) than the case with a gradual distribution that is held fixed (red solid).

4. Summary and Conclusions

- **The primordial internal structure of a giant planet has an important influence on the long-term evolution even after billions of years.**

- **Convection controls the heavy-element distribution and vice versa, as a result, slightly different initial configurations can lead to very different evolutions and final structures.**

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