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Radius Anomaly of Hot Jupiters: Reevaluation of the Possibility and Impact of Layered-Convection

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Masses and radii are fundamental quantities to constrain the compositions of exoplanets. However, observations have revealed that a significant number of close-in gaseous planets (hot Jupiters) have anomalously large radii compared with the theoretical model of planets composed of hydrogen and helium (Baraffe et al., 2010; Baraffe et al., 2014). Understanding of the mechanism of the anomaly is crucial for the estimate of their compositions, and hence, crucial for constraining their formation histories.

Delayed contraction due to compositional inhomogeneity in their interiors has been proposed to explain the radius anomaly (Chabrier & Baraffe, 2007). The compositional inhomogeneity possibly inhibits large-scale-overturning convection and forms small-scale-layered convection which is separated by diffusive interfaces (Rosenblum et al., 2011; Mirouh et al., 2012; Wood et al., 2013). Inefficient heat transport of the layered convection creates a super-adiabatic temperature gradient, which results in the delayed contraction. Chabrier & Baraffe (2007) assumed the presence of the layered convection in the interiors of hot Jupiters, and demonstrated that its effect is sufficient to reproduce the radius anomaly.

However, the layer forms in a limited parameter range described by the reciprocal of the density ratio, Rρ^{-1} = α μ ∇ μ/α_T (∇ $_T$ - ∇ $_{ad}$), where α_T = -(∂ lnρ / ∂ lnT)$_p$,μ, α μ = (∂ lnρ / ∂ lnμ)$_{p,T}$, ∇ $_{ad}$ = (∂ lnT/ ∂ lnp)$_S$,μ, ∇ $_T$ = d lnT/ d lnp, and ∇ μ = d lnμ/ d lnp. The system is unstable for the overturning convection when 0 $<$Rρ^{-1} $<$1. The layered convection or turbulent diffusion occurs when 1 $<$Rρ^{-1} $<$(P$_r$+1)/(P$_r$+τ), where P$_r$ is the Prandtl number and τ is the ratio of compositional to heat diffusivities. The system is stable when Rρ^{-1} $<$0 or (P$_r$+1)/(P$_r$+τ) $<$Rρ^{-1} (Rosenblum et al., 2011; Mirouh et al., 2012; Wood et al., 2013; Leconte & Chabrier, 2012).

We perform an evolutionary calculation of hot Jupiters with a self-consistent treatment of the convection regimes. We calculate the thermal evolution of the interior structures of hot Jupiters with the Henyey method (Kippenhahn et al., 1967). The method solves the equations of the one-dimensional interior structure in hydrostatic equilibrium. The convection regime is determined by the classification based on the density ratio Rρ^{-1}. We use the heat transport model for the overturning convection with the compositional gradient (Umezu & Nakakita, 1988). The transport model developed by Leconte & Chabrier (2012) is adapted for the layered convection.

We show that the impact of the compositional inhomogeneity is limited in the case of monotonic gradient of chemical composition, which is the same setup with Chabrier & Baraffe (2007). The reason for the limited effect is the absence of the layered convection. The convection regime is the overturning convection before $\sim$1 Gyr. In the overturning convection regime, the efficient heat transport forces the temperature gradient to follow the neutrally stable state. Consequently, the super-adiabaticity is limited as ∇ $_T$ $\sim$ ∇ $_{ad}$ + $\alpha\mu$ / α_T ∇ μ. The layer forms only when 1 Gyr passes and the planet is already cooled, but the temperature gradient in this regime is limited as ∇ $_T$ $<\nabla$ $_{ad}$ + $\alpha\mu$ / α_T ∇ μ. Therefore, it is hard to explain the radius anomaly sorely by this mechanism.

Keywords: exoplanet, hot Jupiter, thermal evolution, double-diffusive convection, layered convection