THE EFFECT OF COMPOSITIONAL INHOMOGENEITY ON RADII OF HOT JUPITERS

Hiroyuki Kurokawa[1] and Shu-ichiro Inutsuka[1], [1]Dept. of Phys. Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan (kurokawa@nagoya-u.jp).

Introduction 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 [1, 2]. 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 [3]. The compositional inhomogeneity possibly inhibits large-scale-overturning convection and forms small-scale-layered convection which is separated by diffusive interfaces [4, 5, 6]. Inefficient heat transport of the layered convection creates a super-adiabatic temperature gradient, which results in the delayed contraction. [3] 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,

$$R_\rho^{-1} \equiv \frac{\alpha_\mu \nabla_\mu}{\alpha_T(\nabla_T - \nabla_{\rm ad})}, \qquad (1)$$

where $\alpha_T \equiv -(\partial \ln \rho / \partial \ln T)_{p,\mu}$, $\alpha_\mu \equiv (\partial \ln \rho / \partial \ln \mu)_{p,T}$, $\nabla_{\rm ad} \equiv (\partial \ln T / \partial \ln p)_{S,\mu}$, $\nabla_{\rm T} \equiv {\rm d} \ln T / {\rm d} \ln p$, and $\nabla_\mu \equiv {\rm d} \ln \mu / {\rm d} \ln p$. The system is unstable for the overturning convection when $0 < R_\rho^{-1} < 1$. In this case, large scale convection would smooth out the compositional inhomogeneity in a short time. The layered convection or turbulent diffusion occurs when $1 < R_\rho^{-1} < (P_r + 1)/(P_r + \tau)$, where P_r is the Prandtl number and τ is the ratio of compositional to heat diffusivities. The system is stable when $R_\rho^{-1} < 0$ or $(P_r + 1)/(P_r + \tau) < R_\rho^{-1}$ [4, 5, 6, 7]. Therefore, $R_\rho > 1$ throughout the evolution history is required to create the observed radius anomaly by the delayed contraction due to the compositional inhomogeneity.

We perform an evolutionary calculation with a self-consistent treatment of the convection regimes. Consequently, we show that the impact of the compositional inhomogeneity is limited in the case of monotonic gradient of chemical composition and it is hard to explain the radius anomaly sorely by this mechanism in our setup.

Model We calculate the thermal evolution of the interior structures of hot Jupiters with the Henyey method [8]. 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 R_ρ^{-1} [4, 5, 6, 7]. When $0 < R_\rho^{-1} < 1$, we use the heat transport model for the overturning convection with the compositional gradient [9]. The transport model of the layered convection developed by [7] is adapted when $1 < R_\rho^{-1} < (P_r + 1)/(P_r + \tau)$. When $R_\rho^{-1} < 0$ or $(P_r + 1)/(P_r + \tau) < R_\rho^{-1}$, heat is transported by radiative or conductive diffusion.

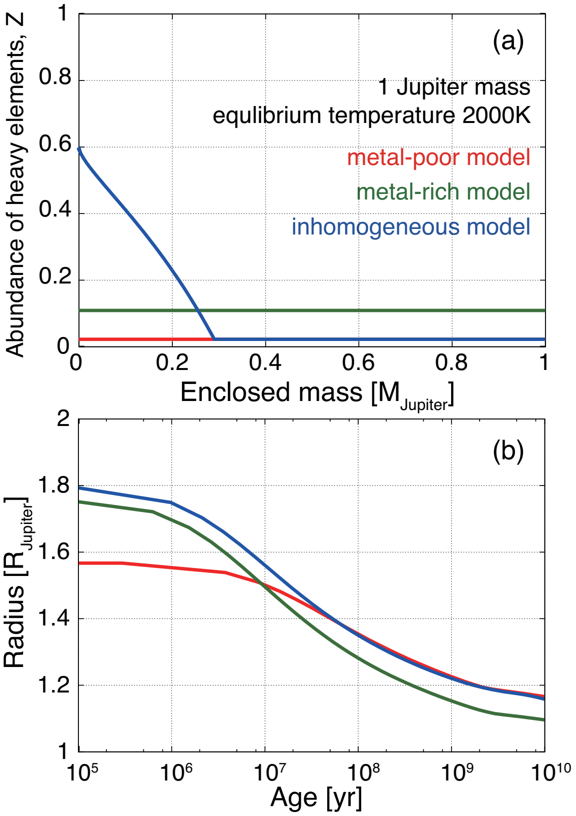

Figure 1: (a) Assumed heavy element profiles in the interiors. (b) Evolution of radii of hot Jupiters.

We use the analytical model of the irradiated atmosphere [10] and the Rosseland mean opacity tabulated by [11]. In the deep interior ($>$ 1 Mbar), the conductive opacity calculated by [12] is used. The equation of state (EOS) of hydrogen and helium is taken from [13] and the EOS of heavy elements (so-called "metals") is represented by SESAME EOS for water [14].

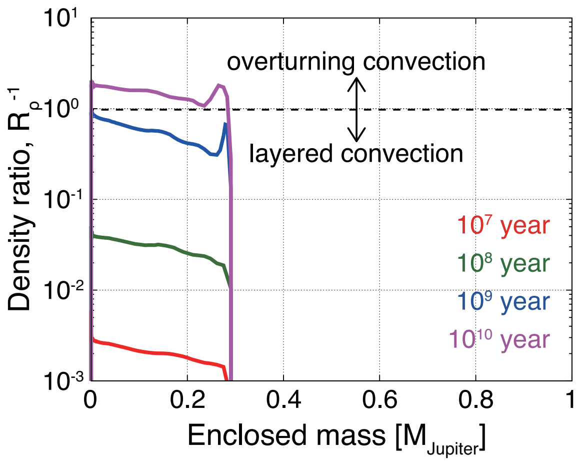

Figure 2: Density ratio profile in the interior in the case of the inhomogeneous model (blue lines in Fig. 1).

We assume 1 Jupiter mass planets and the equilibrium temperature of 2000 K. The mean entropy of $9.5\ k_\mathrm{B}$ baryon^{-1} is assumed for the initial state [15]. We calculate the evolution for three different models: the metal-poor model, metal-rich model, and inhomogeneous model (Fig. 1a). The metal-poor model has protosolar abundance ($Z = 0.02$, where Z is the abundance of heavy elements) throughout the interior. The inhomogeneous model has $\nabla_\mu = 1$ within the inner 30 % by mass similar with the model of [3]. The metal-rich model has the same mass of heavy elements with the inhomogeneous model but assumes its homogeneous distribution. The compositional evolution is not considered.

Results The evolution of the radii of planets is shown in Fig. 1b. They initially have large radii and contract with time because of the cooling. The metal-poor model has a radius larger than 1 Jupiter radius because of the smaller mass of heavy elements and the irradiation. The metal-rich model has a smaller radius than the metal-poor model after $\sim$ 10 Myr due to the larger amount of heavy elements. Because the compositional gradient delays the contraction, the inhomogeneous model has a larger radius than the metal-rich model throughout the evolution. However, the effect of the increased mass of heavy elements negates that of the compositional inhomogeneity on the radius anomaly. As a result, the compositional inhomogeneity cannot reproduce the observed large radius anomaly (up to $\sim$ 2 Jupiter radius).

The reason for the limited effect is the absence of the layered convection. The density ratio in the interior is shown in Fig. 2. The convection regime is the overturning convection before 1Gyr. 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 $\nabla_T \sim \nabla_\mathrm{ad} + \alpha_\mu/\alpha_T \nabla_\mu$. The layer forms only when 1Gyr passes and the planet is already cooled, but the temperature gradient in this regime never exceeds $\nabla_T = \nabla_\mathrm{ad} + \alpha_\mu/\alpha_T \nabla_\mu$.

Discussion Another difficulty to form the layered convection is the turbulent mixing of the compositional inhomogeneity by the overturning convection. The layered convection can preserve the inhomogeneity by the presence of the interfaces of limited diffusivity [3, 7], but the overturning convection should smooth out the compositional structure. To form the layered convection, the compositional inhomogeneity should be formed after planet is cooled enough. Core erosion [16] is one of the possible mechanisms.

Our result suggests that the simple layered convection cannot sorely explain the observed large radius anomaly. As discussed in [1, 2], the solution could be a combination of various processes. Actually, if there is another mechanism to delay the contraction, for instance, atmospheric enhanced opacities [17], it would help the formation of the layered convection by increasing the value of R_ρ^{-1}. Thus, it might be interesting to study the combination of the layered convection with another process to explain the radius anomaly of hot Jupiters.

References

[1] Baraffe, I. et al. (2010) Rep. Prog. Phys., 73, 016901. [2] Baraffe, I. et al. (2014) Protostars and Planets VI, accepted. [3] Chabrier G. & Baraffe I. (2007) ApJL, 661, L81. [4] Rosenblum E. et al. (2011) ApJ, 731, 61. [5] Mirouh G. M. et al (2012) ApJ, 750, 61. [6] Wood T. S. et al. (2013), ApJ, 768, 157. [7] Leconte J. & Chabrier G. (2012) A&A, 540, A20. [8] Kippenhahn, R. et al. (1967) Meth. Comp. Phys., 7, 129-190. [9] Umezu, M. & Nakakita, T. (1988) Astrophys. Space Sci., 150, 115-147. [10] Guillot, T. (2010) A&A, 520, A27. [11] Freedman, R. S. et al. (2008) ApJS, 174, 504-513. [12] Potekhin, A. Y. (1999) A&A, 351, 787-797. [13] Saumon, D. et al. (1995) ApJS, 99, 713-741. [14] Lyon, S. P., & Johnson, J. D. (1992) LANL Rep. LA-UR-92-3407 (Los Alamos: LANL). [15] Marley, M. S. et al. (2007) ApJ, 655, 541-549. [16] Guillot, T. et al. (2004) The interior of Jupiter, Cambridge Univ. Press. [17] Burrows, A. et al. (2007) ApJ, 661, 502-514.