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Kepler-51 系における形成時の水素ヘリウム大気量推定

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Abstract

Due to the progress in observational techniques, we have discovered many exoplanets. The number of multiple systems is increasing year by year. Multiple systems allow us to infer planetary masses by the transit timing variation method. To constrain bulk compositions of planets in multiple systems is important to verify the formation and evolution theory. We constrain the hydrogen-helium mass fraction for planets of Kepler-51 system as an example for a multiple system. While several studies investigated the mass loss evolution of the planets, there are few studies as to investigate the impact of the present intrinsic temperature of the planet. We simulate the interior structure and evolution of highly-irradiated sub/super-Earths that consist of a rocky core surrounded by a hydrogen-helium envelope, which include mass loss due to the stellar XUV-driven energy-limited hydrodynamic escape. We find that the present intrinsic temperature of the planet is important to estimate the present hydrogen-helium mass fraction. We also find there are minimum value for the initial hydrogen-helium mass fraction by the present planet's intrinsic temperature. Minimum values of hydrogen-helium mass fractions for Kepler-51 planets are larger than 10 %. This implies that the halting of the accretion process or the migration process is essential for the origin of Kepler-51 systems.

1 Introduction

Now a days the number of close-in low-mass low-density (LMLD) planets is getting greater due to the high precision observations by space telescopes. Since Kepler space telescope have discovered many types of multiple transit systems, they will tell us the difference between the our solar system and other planetary systems. Small planets are of great interest in their compositions because such LMLD planets do not exist in our solar system. Ikoma & Hori (2012) calculated the accretion of the hydrogen-rich atmosphere of LMLD planets and concluded that LMLD planets which obtained the hydrogen-rich atmosphere in situation had $\lesssim 10$ % by mass. That is, the mass fraction of hydrogen-rich atmosphere for the LMLD planet is essential to understand the formation scenario.

Since LMLD planets which we have known are close to their host star, they have experienced the photo-evaporative mass loss. Several studies showed the impact of the photo-evaporative mass loss on their masses, radii, and compositions (e.g. Valencia et al., 2010, Nettelmann et al., 2011, Lopez et al., 2012, Kurokawa & Kaltenegger 2013, Kurosaki et al., 2014). Owen & Wu (2013) calculated the thermal evolution and mass loss of the LMLD planet which is consisted of a rocky core and a hydrogen-helium (hereafter H-He) envelope simultaneously. They showed the theoretical population of LMLD planets. The theoretical population is consistent with Kepler data. Lopez & Fortney (2013) also calculated smaller mass planets compared to Owen & Wu (2013). They also showed the small mass planets cannot retain their hydrogen-helium envelope for a long period.

Kepler-51 system has extremely low-mass low-density planets. Masuda (2014) showed that the Kepler-51 system has three planets and their mean densities were ~ 0.05 g/cm^3. They would have had significant effect of mass loss. This suggest that

Kepler-51 system possessed more H-He envelope when they were formed. To constrain the initial H-He envelope is important because the H-He mass fraction implies the origin of the planet.

It is important to determine the bulk composition of low-mass low-density planets because the bulk composition, especially the H-He mass fraction, is a clue to solve origins and evolutions of planets. We focus on the H-He mass fraction for Kepler-51 b, c and d via numerical simulation for the thermal evolution and energy-limited mass loss.

2 Method

In this study, we simulate the evolution of the mass and radius of a planet that consists of a H-He envelope and a solid core, including the effects of mass loss due to the photo-evaporation deriven by the XUV flux from the host star. We suppose that the structure is consisted of three layers in spherical symmetry and hydrostatic equilibrium: namely from top to bottom consisted of a H-He atmosphere, a H-He convective envelope and a solid core. We assume the solid core to be rock. In this study, we calculate the thermal evolution and mass loss simultaneously (see Kurosaki et al., 2014 for detail). We use the atmospheric model Guillot (2010) and adopt $\gamma = 0.4$. We assume the He mass fraction in the H-He atmosphere and H-He envelope $Y = 0.25$. We use Freedman et al., (2008) for the atmospheric opacity. We set the initial conditions and calculate backward by time. We stop the calculation if the planet have reached the assumed age or the planetary radius is larger than its Roche lobe radius. We calculate the initial hydrogen helium content of three planets; Kepler-51 b, c and d (see table 1). Here we set parameters: the initial intrinsic temperature $T_{\mathrm{int},0}$ and the age T_a. We assume the age of the Kepler-51 system is equal to that of Kepler-51. We adopt $T_a = 0.3$ Gyr for the age of this system. We assume F_{XUV} as a constant value through the time evolution. In general, F_{XUV} is a function of time and decrease as the time is elapsed. In this study, we adopt $F_{\mathrm{XUV}} = F_0\,(a/1\mathrm{AU})^{-2}$ where $F_0 = 30,100$ erg$\cdot$ s^{-1} $\cdot$ cm^{-2}. We define the equilibrium temperature T_{eq} as $T_{\mathrm{eq}} = T_{\mathrm{eff}}\sqrt{R_\star/(2a)}$ where T_{eff}, $R_\star$, and a are the effective temperature for Kepler-51, the radius for Kepler-51, and the semi-major axis, respectively. We adopt $T_{\mathrm{eff}} = 6018$K, $R_\star = 0.940 R_\oplus$, and a from Table 1.

表 1: Parameter sets for Kepler-51 planets

Name	M_p $[M_\oplus]$	R_p $[R_\oplus]$	a [AU]
Kepler-51 b	2.1	7.1	0.2514
Kepler-51 c	4.0	9.0	0.384
Kepler-51 d	7.6	9.7	0.509

3 Result

Here we show the bulk composition of Kepler-51 planets. First, we derive H-He mass fractions for them in the present day. Second, we derive H-He mass fractions for them when they were formed. Lastly, we explain the reason for the behavior of the H-He mass fraction between the present state and the initial state.

3.1 Present H-He mass fraction

Figure 1 shows the relationship between the present intrinsic temperature T_{int} and the present H-He mass fraction. T_{int} is related to the planetary luminosity as $L_p = 4\pi R_p^2 \sigma T_{\mathrm{int}}^4$ where σ is a Stefan-Boltzmann constant. We find that the present H-He mass fraction increase as the T_{int} decrease. That is because the larger T_{int} causes the larger planetary entropy. The larger planetary entropy causes the thermal expansion of planetary radius and then present H-He mass fraction decrease. We find that H-He mass fractions are 5-65 % for Kepler-51 b, 20-100 % for Kepler-51 c, and 30-100 % for Kepler-51 d. If the H-He mass fraction for each planet is

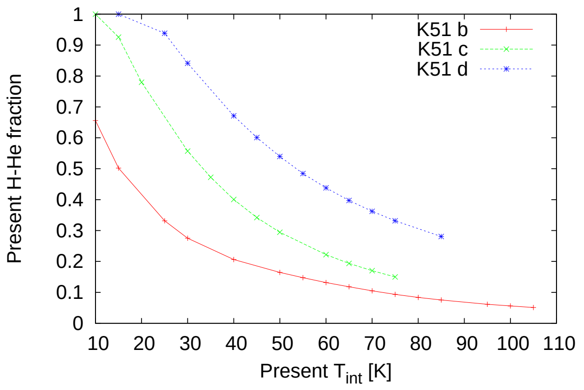

図 1: Relationships between the present $T_{\rm int}$ and present H-He mass fractions. The red, green, and blue are Kepler-51 b, c, and d, respectively.

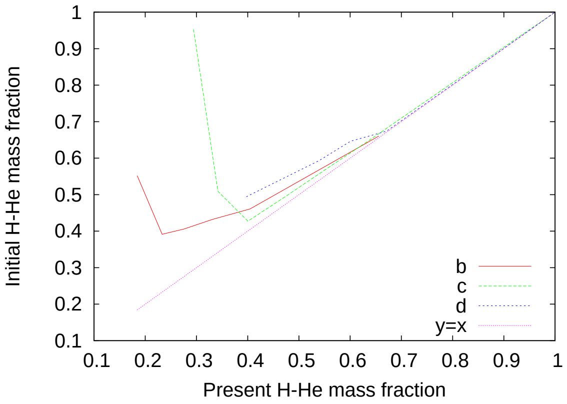

図 2: Relationships between the present and initial H-He mass fractions for $F_0 = 100$. The red, green, and blue are Kepler-51 b, c, and d, respectively.

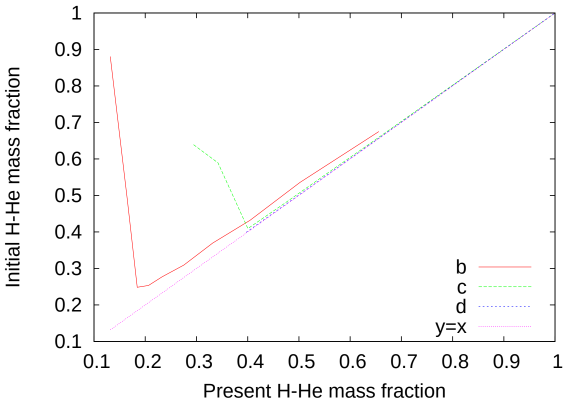

図 3: Relationships between the present and initial H-He mass fractions for $F_0 = 30$. The red, green, and blue are Kepler-51 b, c, and d, respectively.

less than the lower limit for each planet, the age of the planet is inconsistent.

3.2 Initial H-He mass fraction

Although uncertainty of the mass loss theory and the initial heat content unable us to determine the upper limit of initial H-He content, we find that there are minimum value for the initial H-He content by the present H-He content. Figure 2 shows relationships between present H-He mass fractions and initial planetary masses for $F_0 = 100$. Figure 3 shows relationships between present H-He mass fractions and initial planetary masses for $F_0 = 30$. In general, the present H-He content is a function of the present intrinsic luminosity. That is, the planet's H-He content is small if the present intrinsic luminosity is high due to the high entropy of the planet. Although we cannot remove the uncertainty of XUV flux and the water mass fraction, we have removed the uncertainty of the minimum H-He content. This minimum value for H-He content X_H^* will be useful to constrain the formation scenario. Supposed $30 \leq F_0 \leq 100$ by the time evolution, we find that $X_H^* = 20-35$ % for Kepler-51 b, $X_H^* = 35-40$ % for Kepler-51 c. However, we cannot find X_H^* for Kepler-51 d because the mass loss does not affect significantly.

3.3 Existence for the minimum value

The reason why there are minimum values for initial H-He mass fractions is the balance between the mass loss timescale and thermal contraction. The most important effect for the existence of the minimum value is the expansion rate of a hydrogen-helium planet. The expansion rate is a function of the planetary mass, H-He mass fraction and the planetary intrinsic temperature supposed the semi-major axis is constant. If the present H-He mass fraction is small, the present intrinsic temperature is large. Then the planet is easy to expand, which causes the significant mass loss. On the other hand, the large H-He mass fraction is due to the small present intrinsic temperature. Then the planet does not expand enough to cause the significant mass loss. In figure 2 and 3, $y = x$ means that the planet have not experienced significant mass loss.

4 Discussion

4.1 Uncertainty of the XUV flux

We evaluate the uncertainty of the X-ray flux. Since we have little knowledge about the XUV flux of the Kepler-51, we evaluate the 8 types of X-ray model derived by Jackson et al., (2012). However, the difference of X-ray model does not affect the value of X_H^* significantly. Therefore, $X_H^* > 10$ % for Kepler-51 planets is valid.

4.2 The orbital stability of Kepler-51 system

For Kepler-51 system, the mutual Hill radius Δ is larger than 9. Chambers et al., (1996) showed that the multiple system for $\Delta > 9$ is stable for a long periods. Although Chambers et al., (1996) assumed planetary masses are constant value, this conclusion does not change when we assume $e = 0$. Therefore, Kepler-51 system has no problem in the orbital stability if they experienced significantly mass loss.

5 Conclusion

We constrain the hydrogen-helium mass fraction for planets in the Kepler-51 system. We can derive the minimum mass fraction for the hydrogen-helium mass fraction. Minimum values of hydrogen-helium mass fractions for these planets are larger 10 %. Although we need evaluate the sensitivity of the composition of core and atmosphere, this implies that Kepler-51 system have not been likely to formed in situ and the halting the accretion of atmosphere and the migration process are essential to constrain the origin of the Kepler-51 system.

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