MASS-LOSS EVOLUTION OF CLOSE-IN EXOPLANETS: EVAPORATION OF HOT JUPITERS AND THE EFFECT ON POPULATION

H. KUROKAWA and T. NAKAMOTO

1 Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan; kurokawa@nagoya-u.jp
2 Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

Received 2013 September 30; accepted 2014 January 11; published 2014 February 12

ABSTRACT

During their evolution, short-period exoplanets may lose envelope mass through atmospheric escape owing to intense X-ray and extreme ultraviolet (XUV) radiation from their host stars. Roche-lobe overflow induced by orbital evolution or intense atmospheric escape can also contribute to mass loss. To study the effects of mass loss on inner planet populations, we calculate the evolution of hot Jupiters considering mass loss of their envelopes and thermal contraction. Mass loss is assumed to occur through XUV-driven atmospheric escape and the following Roche-lobe overflow. The runaway effect of mass loss results in a dichotomy of populations: hot Jupiters that retain their envelopes and super Earths whose envelopes are completely lost. Evolution primarily depends on the core masses of planets and only slightly on migration history. In hot Jupiters with small cores (≤10 Earth masses), runaway atmospheric escape followed by Roche-lobe overflow may create sub-Jupiter deserts, as observed in both mass and radius distributions of planetary populations. Comparing our results with formation scenarios and observed exoplanets populations, we propose that populations of closely orbiting exoplanets are formed by capturing planets at/inside the inner edges of protoplanetary disks and subsequent evaporation of sub-Jupiters.

Key words: planets and satellites: atmospheres – planets and satellites: composition – planets and satellites: physical evolution – stars: activity

1. INTRODUCTION

To date, hundreds of extrasolar planets and thousands of Kepler planet candidates have been detected and their statistical properties have been widely investigated (e.g., Howard et al. 2010, 2012). Orbital period has been negatively correlated with planetary mass, surface gravity, and mean density (e.g., Mazeh et al. 2005; Southworth et al. 2007; Jackson et al. 2012). A negative correlation between orbital period and planetary mass was first reported by Mazeh et al. (2005); however, only a relatively small number of planets were detected at that time. A negative correlation between orbital period and surface gravity was later reported by Southworth et al. (2007). These correlations persisted in studies conducted more recently because the number of observed exoplanets has increased (Wu & Lithwick 2013; Weiss et al. 2013). With the detection of inner-orbit super Earths, which are clearly separate from the hot Jupiters, researchers recognized the so called “desert of sub-Jupiter size exoplanets” at orbital periods of <3 days in the orbital period–mass diagram (Szabó & Kiss 2011; Beaugé & Nesvorný 2013). This orbital period corresponds to the orbits of <0.04 AU around solar-mass stars. The desert has also been found in the orbital period–radius diagram at radii and orbital periods of 3–10 R_{Earth} and <3 days, respectively, which include Kepler planet candidates (Beaugé & Nesvorný 2013).

According to the population synthesis of planet formation theory, a sub-Jupiter should occur within ≤1 AU, which originates in gas planet formation at far orbits and planet migration (e.g., Ida & Lin 2008; Mordasini et al. 2009, 2012). However, statistical analysis of exoplanets revealed that this region is full of planets and the observed desert inside ≤0.04 AU is more compact than predicted (Howard et al. 2010, 2012). Beaugé & Nesvorný (2013) attributed the compact sub-Jupiter desert to three possible mechanisms. One of these mechanisms, evaporation of sub-Jupiters by intensive atmospheric escape, is investigated in our study. The other mechanisms are planet capture at/inside the disk inner edge and interplanetary scattering followed by tidal capture of a planet by its host stars. These scenarios are compared with the evaporation scenario in Section 4.

Jackson et al. (2012) showed that orbital period may be correlated with planetary mass if the mass is thermally evaporated by X-ray and extreme ultraviolet (XUV) radiation (see, e.g., Lammer et al. 2003). This scenario is applicable to the sub-Jupiter desert as Beaugé & Nesvorný (2013) proposed. Jackson et al. (2012) adopted a simple energy-limited escape approach (Watson et al. 1981) and assumed a constant radius or density during planetary evolution. The energy-limited escape has been widely used in mass-loss evolution studies (Lammer et al. 2003; Baraffe et al. 2004; Hubbard et al. 2007; Valencia et al. 2010; Jackson et al. 2010; Jackson et al. 2012; Leitzinger et al. 2011; Kurokawa & Kaltenegger 2013; Lopez & Fortney 2013), in which the energy of XUV photons efficiently supplies the escape energy. However, models of the upper atmosphere of closely orbiting exoplanets have shown that the escape regime deviates from the energy-limited regime under extremely high XUV scenarios (Murray-Clay et al. 2009; Guo 2011; Owen & Jackson 2012). Under these conditions, some of the XUV energy is lost as Lyα radiation from excited hydrogen atoms; this effect is called “radiation-recombination-limited escape.” Also, mass loss could cause envelope expansion, which further accelerates mass loss (Baraffe et al. 2004; Kurokawa & Kaltenegger 2013). The evolution of planetary mass and radius must be considered to account for this runaway effect. Mass loss eventually lead to Roche-lobe overflow, in which the envelope is dynamically eroded from the Roche lobe and a catastrophic evaporation occurs (Kurokawa & Kaltenegger 2013).

In this study, we examine how mass loss progresses in inner exoplanets and the consequent effects on exoplanet populations in terms of XUV-driven atmospheric escape and Roche-lobe overflow. Our model extends the model of Kurokawa & Kaltenegger (2013), which solves the evolution of planetary mass and radius. This model enables the effects of...
runaway mass loss and the Roche-lobe overflow to be observed. We newly account for radiation-recombination-limited escape by developing a semianalytical model of the upper atmosphere. Our numerical models are introduced in Section 2. Section 3 presents our results and compares them with observed exoplanet populations. Section 4 shows comparisons with previous studies on mass-loss evolution, discusses the sensitivity of the results to the model assumptions, compares our proposed mechanism with other possible mechanisms of the sub-Jupiter desert, and presents some implications for planet formation scenarios. Section 5 concludes the study.

2. NUMERICAL MODELS

The planet is assumed to be spherically symmetric, with a solar composition envelope and a rock/iron core. We adopt the Rosseland mean opacity of solar composition gas (Freedman et al. 2008) but use the equation of state (EoS) of hydrogen and helium (Y = 0.28) from the data tables in Saumon et al. (1995). We introduce two updates to the model of Kurokawa & Kaltenegger (2013).

The first update introduces the effects of core contraction and its internal heat. The EoS in the core and the required physical constants are taken from Wagner et al. (2011), assuming a rock-to-iron mass ratio of 0.675:0.325. For the upper silicate mantle, we use the Vinet EoS (Vinet et al. 1989):

\[
p = 3K_0x^3(1-x^{-\frac{3}{2}}) \exp \left[ \frac{2}{3}(K_0' - 1)(1 - x^{-\frac{3}{2}}) \right].
\]  

(1)

where \( p \) is the pressure, \( x = \rho/\rho_0 \) is the compression ratio with respect to the ambient density \( \rho_0 \), \( K_0 \) is the isothermal bulk modulus, and \( K_0' \) is the pressure derivative of \( K_0 \). The subscript 0 denotes the ambient conditions. The higher pressure phases of perovskite, post-perovskite, and the iron core are treated by the generalized Rydberg EoS (Wagner et al. 2011):

\[
p = 3K_0x^{\infty}(1-x^{-\frac{3}{2}}) \exp \left[ \frac{3}{2}K_0' - 3K_\infty + \frac{1}{2}(1 - x^{-\frac{3}{2}}) \right],
\]  

(2)

where the subscript \( \infty \) denotes the limit of infinitely large pressure. To incorporate the contribution of the core heat, Equation (9) in Kurokawa & Kaltenegger (2013) is substituted by the energy conservation equation (e.g., Lopez et al. 2012):

\[
\int_{M_{\text{core}}}^{M_p} T \frac{dS}{dt} dM_r = L_{\text{int}} - L_{\text{radio}} - C_p \frac{dT_{\text{core}}}{dt}.
\]  

(3)

On the left-hand side of Equation (3), \( M_p \), \( M_{\text{core}} \), and \( M_r \) denote the planetary mass, the core mass, and the enclosed mass at a distance \( r \), respectively. \( T \) is the temperature, \( S \) is the entropy in the convective layer of the envelope, and \( t \) is the time. On the right-hand side, \( R_p \) and \( L_{\text{int}} \) denote the radius and the intrinsic luminosity of the planet, respectively, \( L_{\text{radio}} \) is the rate of heat production by the radioactive elements in the rocky layer, \( C_p \) is the heat capacity of the core, and \( T_{\text{core}} \) is the temperature at the top of the core. The abundance of radioactive elements to calculate \( L_{\text{radio}} \) and the value of \( C_p \) are assumed to be the same as those in Yukutake (2000).

The other update is the mass loss due to atmospheric escape. To accommodate this loss, we consider the transition from the energy-limited escape to the radiation-recombination-limited regime. The rate of mass loss is calculated for each regime and the regime yielding the smaller rate is assumed. This scheme smoothly connects the radiation-recombination escape induced by high XUV to the energy-limited escape under lower XUV conditions. The Roche-lobe overflow induced by the atmospheric escape is calculated as described in Kurokawa & Kaltenegger (2013).

Under lower XUV conditions, the energy-limited escape is modeled by the formula of Lopez et al. (2012), given by

\[
\frac{dM_p}{dt} = \eta \frac{F_{\text{XUV}} R_{\text{XUV}}^3}{GM_p K_{\text{tide}}},
\]  

(4)

where \( \eta \) is the efficiency, \( F_{\text{XUV}} \) is the incoming XUV energy flux, \( R_{\text{XUV}} \) is the radius of XUV photon absorption, \( G \) is the gravitational constant, and \( K_{\text{tide}} \) is a tidal correction factor. Of these parameters, only the XUV radius \( R_{\text{XUV}} \) is calculated differently from Kurokawa & Kaltenegger (2013), who assumed a thin layer between \( R_p \) and \( R_{\text{XUV}} \). Following Lopez et al. (2012), we calculated an isothermal structure from \( R_p \) to \( R_{\text{XUV}} \) and defined \( R_{\text{XUV}} \) at the 1 nbar level. We neglected photochemical processes, which complicate the temperature structure in the upper atmosphere. This procedure yielded a rough estimate of the XUV radius \( R_{\text{XUV}} \). The influence is evaluated in Section 4.

Higher XUV conditions are treated in a semianalytical model of the radiation-recombination-limited escape. The model is based on the analytical approach of Murray-Clay et al. (2009), which accounts for tidal and nonhydrostatic effects. In the radiation-recombination-limited regime, the hydrogen atmosphere above \( R_{\text{XUV}} \) is almost fully ionized by XUV radiation and holds \( \sim 10^4 \) K by Ly\textsc{a} radiation emitted from excited hydrogen atoms. Here, we model the regime as an isothermal transonic flow. The rate of mass loss at the sonic point is given by

\[
\frac{dM_p}{dt} = 4\pi \rho_s w_s r_s^2,
\]  

(5)

where the subscript \( s \) denotes the sonic point and \( w_s \) is the upward velocity, which is equal to the isothermal sound speed \( c_T \) of ionized hydrogen gas at \( 10^4 \) K. The radius at the sonic point \( r_s \) is calculated as

\[
2r_s^2 = \frac{GM_p}{r_s} - 3\frac{GM_{\text{star}}r_s^2}{a^3},
\]  

(6)

where the second term on the right-hand side represents the tidal contribution. Here, \( M_{\text{star}} \) is the mass of the host star and \( a \) is the orbital radius. The density at the sonic point is obtained from the isothermal structure equation:

\[
\rho_s = \rho_{\text{base}} \exp \left[ -\frac{GM_{\text{star}}}{c_T^2} \left( r_s^{-1} - r_{\text{base}}^{-1} \right) - \frac{1}{2} + \frac{1}{2} \left( \frac{w_{\text{base}}}{c_T} \right)^2 \right] + \frac{3GM_{\text{star}}}{2a^3c_T^2} \left( r_s^2 - r_{\text{base}}^2 \right),
\]  

(7)

where the subscript “base” denotes the base of the flow, which corresponds to \( R_{\text{XUV}} \). The density at the base is the balance between photoionization and radiative recombination (Murray-Clay et al. 2009):

\[
\frac{F_{\text{XUV}}}{h v_0} \sigma_{\alpha}\sigma_{\alpha,\text{base}} = n_{\text{e,base}}^2 \alpha_{\text{rec}},
\]  

(8)
where $h_{\nu_0}$ is photon energy ($\sim$20 eV), $\sigma_{\nu_0}$ is the cross section for photoionization of hydrogen, $n_0$ and $n_+$ are the number densities of neutral and ionized hydrogen, respectively, and $\sigma_{\text{rec}} = 2.7 \times 10^{-13}$ cm$^3$ s$^{-1}$ is the radiative recombination coefficient for hydrogen ions. The neutral number density at the base $n_{0,\text{base}}$ is estimated by

$$n_{0,\text{base}} \sim \frac{1}{\sigma_{\nu_0} H_{\text{base}}} \sim \frac{m_{\text{H}} \rho_{\text{base}}}{2 \sigma_{\nu_0} k_B T}, \tag{9}$$

where $H$ is the scale height, $g$ is the gravitational acceleration, and $k_B$ is the Boltzmann constant. Equations (5)–(9) provide the rate of mass loss in the radiation-recombination regime. If the solar analogs and which assumes a typical saturation phase of 1 Gyrs (Jackson et al. 2012). The mass-loss rate $M$ yr$^{-1}$ is given by

$$M = M_{\text{planet}} = M_{\text{Jupiter}},$$

where $R_{\text{XUV}} = R_{\text{Jupiter}}$, respectively. Results are plotted at semi-major axes of 0.015 AU, 0.02 AU, 0.03 AU, 0.1 AU, and 10 AU (ordered from top to bottom).

Figure 1. Rate of mass loss by thermal atmospheric escape. The mass and radius of the planets are $M_p = 1 M_{\text{Jupiter}}$ and $R_{\text{XUV}} = 1 R_{\text{Jupiter}}$, respectively. Results are plotted at semi-major axes of 0.015 AU, 0.02 AU, 0.03 AU, 0.1 AU, and 10 AU (ordered from top to bottom).

Figure 2. Rate of mass loss by thermal atmospheric escape. The planetary mass is $M_p = 1 M_{\text{Jupiter}}$. Results are plotted for planetary radii $R_{\text{planet}} = 2$, 1.5, and 1 $R_{\text{Jupiter}}$ (ordered from top to bottom). The semi-major axis of the planets is 0.02 AU.

$R_{\text{XUV}} = R_{\text{fit}}$. We calculate the evolution of migrated planets as well as planets formed in situ. Migrated planets that formed in outer regions cool more rapidly and possess lower entropy than their in situ counterparts. To capture their migration history, we assign a different initial entropy to migrated planets. On the basis of thermal evolution calculations, the initial entropy of planets above and below 200 $M_{\text{Earth}}$ is assumed to be 8.5 $k_B$ baryon$^{-1}$ and 8 $k_B$ baryon$^{-1}$, respectively (see Section 3 for details).

3. RESULTS

3.1. Properties of Mass-loss Evolution

To observe the effects of stellar irradiation on thermal evolution, which is related to planetary migration history, we first simulated the thermal evolution without mass loss at different orbital radii. The results are presented in Figures 3 and 4. As planets cool, their large initial radii gradually shrink. Planets orbiting closer to their parent star maintain larger radii because they receive heat from stellar radiation, which in turn reduces their cooling rate. In addition, the radii of low-mass planets are more susceptible to cooling effects than those of heavier planets. Low-mass planets are highly inflated in their nascent stages, i.e., when they are hot, which affects their mass-loss evolution, as shown later. The initial entropy in the migrated model can be estimated from Figure 4. Planetary migration induced by interaction with protoplanetary disk gas should terminate when the disk dissipates. Assuming that migrated planets form at distant orbits ($\sim$1–10 AU) and migrated 10$^7$ yr later, the initial entropy of migrated planets above and below 200 $M_{\text{Earth}}$ is estimated as 8.5 $k_B$ baryon$^{-1}$ and 8 $k_B$ baryon$^{-1}$, respectively.

The mass-loss evolution and the effect of the orbital radius are shown in Figure 5. The planets are 200 $M_{\text{Earth}}$ with core masses of 10 $M_{\text{Earth}}$. Planets with semi-major axes below 0.019 AU are completely evaporated within 10 Gyrs. Although we account for radiation-recombination-limited escape, which weakly depends on XUV insolation ($F_{\text{XUV}}^{1/2}$) and which reduces the mass-loss rate, complete evaporation is possible. Models in which the atmosphere escapes solely by energy-limited-thermal escape also permit total evaporation (Baraffe et al. 2004; Valencia et al. 2010; Jackson et al. 2010; Kurokawa & Kaltenegger 2013).
Figure 3. Evolution of the radius of gas planets assuming no mass loss. All core masses are $10 M_{\text{Earth}}$. Planetary masses are (a) $300 M_{\text{Earth}}$, (b) $250 M_{\text{Earth}}$, (c) $200 M_{\text{Earth}}$, (d) $150 M_{\text{Earth}}$, (e) $100 M_{\text{Earth}}$, and (f) $50 M_{\text{Earth}}$. Planetary orbits are 0.015 AU (solid line), 0.1 AU (dashed line), 1 AU (dotted line), and 10 AU (dash-dotted line). Initial entropies are $9.2 \, k_{\text{B}}$ baryon$^{-1}$, except for the 50 $M_{\text{Earth}}$ planet at 0.015 AU, for which no hydrostatic solution exists for the initial entropy. In this case, a lower initial entropy that admits a hydrostatic solution is assumed.

In the event of complete evaporation, the planets lose large quantities of their envelopes in the radiation-recombination-limited regime (Figure 5). Once a planet enters the energy-limited regime, it loses mass at a much slower rate. Because this regime strongly depends on the XUV flux ($F_{\text{XUV}}$), the temporal decline of the stellar XUV radiation markedly affects the rate of mass loss. Besides the thermal atmospheric escape, Roche-lobe overflow contributes to the complete evaporation. Once Roche-lobe overflow occurs, most of the planet’s envelope is lost. The remnant (a thin envelope of mass $< 1 M_{\text{Earth}}$) dissipates by thermal atmospheric escape over a short timescale. Planets with slightly larger semi-major axes (in this case, $>0.02$ AU) retain most of their envelopes and remain as hot Jupiters. As explained below, this phenomenon is attributable to lower mass-loss rates at distant orbits and the runaway nature of mass loss.

Figure 6 shows how the planetary radius, the XUV radius, and the Roche-lobe radius evolve if the planet’s envelope completely evaporates. The Roche-lobe radius decreases with mass. The planetary radius changes less dramatically and the XUV radius enlarges prior to Roche-lobe overflow as the gravity declines. The expansion due to mass loss is a general property of hot planets with moderately high-mass envelopes, as observed in Figure 7, which plots the planetary radius as a function of envelope mass. During early-stage cooling, the planetary and XUV radii are both reduced. The cooling timescale lengthens as cooling progresses (see Figures 3 and 4). At later stages of the evolution, when the cooling timescale exceeds the timescale of mass loss, the planet expands as it loses mass. This mechanism leads to runaway thermal atmospheric escape followed by Roche-lobe overflow (Baraffe et al. 2004; Kurokawa & Kaltenegger 2013). Because a moderate amount of the envelope is insecurely bound, Roche-lobe overflow inflates the radius, leaving a thin envelope surrounding the core (Figure 7). Following Roche-lobe overflow, the radius suddenly decreases as most of its envelope is lost.

The mass-loss evolution of hot Jupiters with the same semi-major axis but different initial masses is shown in Figure 8. From slightly varying initial masses, a dichotomous population evolves: planets with completely evaporated envelopes versus those remaining as hot Jupiters. This dichotomy occurs because the radii of heavier planets are smaller in the Jupiter-mass regime (Figure 7) and thus lose mass more slowly. The difference between the populations is amplified throughout the evolution by runaway thermal atmospheric escape and the Roche-lobe
Figure 4. Evolution of the entropy of gas planets assuming no mass loss. Core masses are $10 \, M_{\text{Earth}}$. Planetary masses are (a) $300 \, M_{\text{Earth}}$, (b) $250 \, M_{\text{Earth}}$, (c) $200 \, M_{\text{Earth}}$, (d) $150 \, M_{\text{Earth}}$, (e) $100 \, M_{\text{Earth}}$, and (f) $50 \, M_{\text{Earth}}$. Planetary orbits are $0.015 \, \text{AU}$ (solid line), $0.1 \, \text{AU}$ (dashed line), $1 \, \text{AU}$ (dotted line), and $10 \, \text{AU}$ (dash-dotted line). Initial entropies are $9.2 \, k_{\text{B}} \, \text{baryon}^{-1}$, except for the $50 \, M_{\text{Earth}}$ planet at $0.015 \, \text{AU}$, for which no hydrostatic solution exists for the initial entropy. In this case, a lower initial entropy that admits a hydrostatic solution is assumed.

Figure 5. Mass evolution of $200 \, M_{\text{Earth}}$ planets as functions of time. The semi-major axes range from $0.018 \, \text{AU}$ to $0.022 \, \text{AU}$ in $0.001 \, \text{AU}$ increments. All core masses are $10 \, M_{\text{Earth}}$ (indicated by the dashed line). Filled circles indicate the changeover times of the atmospheric escape regime, from radiation-recombination limited to energy limited. The second circle at $0.019 \, \text{AU}$ marks the transition from the energy-limited regime to the radiation-recombination-limited regime. Crosses indicate Roche-lobe overflow events.

Figure 6. Radial evolution of a $200 \, M_{\text{Earth}}$ planet as a function of time. The semi-major axis is $0.018 \, \text{AU}$ and the core mass is $10 \, M_{\text{Earth}}$. Shown are the planetary radius (solid line), the XUV radius (dashed line), and the Roche-lobe radius (dotted line). The dash-dotted line indicates the core radius. The cross marks Roche-lobe overflow events.
Figure 7. Planetary radii as functions of envelope mass. Core masses and semi-major axes are (a) $10 \, M_{\text{Earth}}$ and 0.015 AU, (b) $10 \, M_{\text{Earth}}$ and 0.1 AU, (c) $10 \, M_{\text{Earth}}$ and 1.0 AU, (d) $10 \, M_{\text{Earth}}$ and 10 AU, (e) $20 \, M_{\text{Earth}}$ and 0.015 AU, and (f) $30 \, M_{\text{Earth}}$ and 0.015 AU. Results (solid lines) are plotted for different entropies in the convective layer $S_{\text{convective}} = 9, 8, 7,$ and $6 \, k_{B} \, \text{baryon}^{-1}$ (ordered from top to bottom).

Figure 8. Mass evolution of hot Jupiters as a function of time. All semi-major axes are 0.02 AU and core masses are $10 \, M_{\text{Earth}}$ (indicated by the dashed line). Results are plotted for planetary masses $300 \, M_{\text{Earth}}, 250 \, M_{\text{Earth}}, 200 \, M_{\text{Earth}}, 150 \, M_{\text{Earth}},$ and $100 \, M_{\text{Earth}}$ (ordered from top to bottom). Filled circles indicate the changeover times of the atmospheric-escape regime; from radiation-recombination limited to energy limited. Crosses indicate Roche-lobe overflow events.
mass-loss evolution than migration history. The relationships between envelope mass and planetary radius for different core masses and semi-major axes are 0.015 AU. The planets formed in situ have core masses 10 $M_{\text{Earth}}$ (solid line) and 30 $M_{\text{Earth}}$ (dashed line). The core mass of the migrated planet is 10 $M_{\text{Earth}}$ (dotted line). The dash-dotted line indicates the mass of the 10 $M_{\text{Earth}}$ core. Filled circles indicate the changeover times of the atmospheric-escape regime, from radiation-recombination limited to energy limited. The second circle in the migrated case marks the transition from the energy-limited regime to the radiation-recombination-limited regime. Crosses indicate Roche-lobe overflow events.

**Figure 9.** Mass evolution of 290 $M_{\text{Earth}}$ planets as a function of time. All semi-major axes are 0.015 AU. The planets formed in situ have core masses 10 $M_{\text{Earth}}$ (solid line) and 30 $M_{\text{Earth}}$ (dashed line). The core mass of the migrated planet is 10 $M_{\text{Earth}}$ (dotted line). The dash-dotted line indicates the mass of the 10 $M_{\text{Earth}}$ core. Filled circles indicate the changeover times of the atmospheric-escape regime, from radiation-recombination limited to energy limited. The second circle in the migrated case marks the transition from the energy-limited regime to the radiation-recombination-limited regime. Crosses indicate Roche-lobe overflow events.

**Figure 10.** Evolution of the XUV radii $R_{\text{XUV}}$ of Jupiter-mass (290 $M_{\text{Earth}}$) planets as functions of time. The settings are described in the caption of Figure 9. The dash-dotted line indicates the radius of a 10 $M_{\text{Earth}}$ core.

**Figure 11.** Minimum survival mass as a function of semi-major axis. The solid line is the result of planets that have 10 $M_{\text{Earth}}$ cores and are formed in situ, the dash-dotted line is the same as the solid line except for the assumption of energy-limited escape, the dotted line is the result of planets that have 10 $M_{\text{Earth}}$ cores and are migrated, and the dashed line is the result of planets that have 30 $M_{\text{Earth}}$ cores and are formed in situ. Note that the solid and the dotted lines (10 $M_{\text{Earth}}$ core; in situ formation and migrated) almost overlap.

3.2. Comparison with Exoplanet Populations

By calculating mass-loss evolution at different planetary masses and semi-major axes, we can obtain the minimum survival mass as a function of semi-major axis. Within a suitable evolution time (here, we assumed 10 Gyr), planets heavier than the critical mass are robust to mass loss, while lighter planets lose their entire envelope and become naked solid-core planets. For example, the minimum survival mass of in situ planets with semi-major axes 0.02 AU and core masses 10 $M_{\text{Earth}}$ is 200 $M_{\text{Earth}}$ (Figure 8). Minimum survival masses are plotted as functions of semi-major axis in Figure 11. The results for different scenarios are shown. Note that the survival mass is calculated to two significant digits. The fiducial model comprises in situ-formed planets of core mass 10 $M_{\text{Earth}}$. As shown in Section 3.1, core mass exerts significant effects on the mass-loss evolution. Because planets with heavy cores are robust against envelope loss, their survival masses are smaller than those of lighter-core planets. Migrated planets, with their smaller entropy and radii, are more stable than the fiducial model. Consequently, their survival mass is decreased, but only slightly. For comparison, the model excluding radiation-recombination-limited escape (in which the envelope is lost by energy-limited escape and Roche-lobe overflow alone) is also shown. In general, radiation-recombination-limited escape reduces the rate of mass loss, especially at larger semi-major axes. At small semi-major axes (<0.03 AU), the original and refined models yield very similar results. Under these conditions, the rate of mass lost by radiation-recombination-limited escape is enhanced by tidal effects (Figure 1).

Figure 12 compares the predicted minimum survival masses with the observed exoplanet populations. Although the differences among host stellar properties are ignored in this figure, the majority of observed exoplanets orbit G-type stars, as
assumed in our model. In the observed population, the desert of sub-Jupiter mass planets occurs at close orbits (≤0.04 AU) and a planetary mass of ≃100 M_{Earth}. The minimum survival masses of planets of core mass 10 M_{Earth} are consistent with the observed desert. Planets heavier than the survival mass also lose some mass, thereby moving down in mass-distribution diagram. As observed in Figure 8, however, slight differences in the initial mass cause large differences in final mass because mass loss is a runaway process. Thus, we can neglect the mass loss of planets heavier than the survival mass and directly compare the predicted line with the observed desert. The survival masses of the heavier-core models (20 M_{Earth}, 30 M_{Earth}) are lower than that of the lighter-core model (10 M_{Earth}). The lines of heavier-core models do not match the observed desert. Therefore, our results indicate that hot Jupiters tend to have small cores (≤10 M_{Earth}). A core mass of 10 M_{Earth} is consistent with the typical mass of super Earths at the semi-major axis of the desert at ≤0.04 AU. Some of these super Earths may be remnants of evaporated sub-Jupiter mass exoplanets. Beyond a semi-major axis of =0.04 AU, the mass distribution of exoplanets does not significantly depend on mass loss.

Next, we compare our results with the observed radii of exoplanets. The observed distribution of planetary radii comprising both confirmed planets and Kepler planet candidates is shown in Figure 13. Planets of sub-Jupiter radius are sparse in the range of ≃3–10 R_{Earth} and ≤0.04 AU. Two confirmed planets in this cavity are known to orbit M-type stars and should thus be excluded from the discussion. Moreover, as indicated by Beaugé & Nesvorný (2013), all 16 candidates found in the desert occupy single-planet systems. The false-positive detection rates of single-planets systems are higher than those of multiple-planet systems and at least seven of the desert candidates may be false positives (Beaugé & Nesvorný 2013), which would obscure the desert boundaries. Planets larger than 10 R_{Earth} and smaller than 3 R_{Earth} can be regarded as hot Jupiters and super Earths, respectively; the latter are devoid of massive envelopes. Assuming a core mass of 10 M_{Earth} (consistent with the sub-Jupiter mass desert), radii of 3–10 R_{Earth} correspond to envelope masses of <10 M_{Earth} at close orbits(<0.04 AU), as shown in Figure 7. However, because the masses of these planets are below the minimum survival masses, their envelopes could be evaporated. Therefore, our results suggest that mass loss may be responsible for the dearth of planets with sub-Jupiter radii.

4. DISCUSSION

4.1. Comparison with Previous Studies

Recently, mass-loss evolution of close-in exoplanets was studied by Owen & Wu (2013) and Lopez & Fortney (2013). The model of Lopez & Fortney (2013) is similar to ours but the radiation-recombination-limited escape is not included. The model of Owen & Wu (2013) used a rate of mass loss obtained by their hydrodynamic simulation and their XUV model is different. Although these studies mainly concerned low-mass planets, a few examples of heavier planets were studied. Owen & Wu (2013) showed the evolution of a Jupiter mass (318 M_{Earth}) planet with a 15 M_{Earth} core at 0.025 AU in their Figure 2 and concluded that the mass loss was small compared with the total mass (~0.5% of the total mass is lost after 10 Gyr). The heaviest planet from calculations by Lopez & Fortney (2013) is a 320 M_{Earth} planet with a 64 M_{Earth} core at ~0.033 AU (converted from an assumed incident flux 1000 times larger than that Earth receives) in their Figure 2, which does not lose significant mass. In our fiducial model (with a 10 M_{Earth} core and including the radiation-recombination-limited escape), a high-mass planet (290 M_{Earth}, nearly a Jupiter mass) completely evaporates at a quite close-in orbit (0.015 AU; our Figure 9).

We compare our results with these examples of high-mass planets in Owen & Wu (2013) and Lopez & Fortney (2013) and conclude that the main cause for the difference of results is the difference in the assumed separation from the host star. The amount of mass loss strongly depends on the assumed separation. Planets orbiting at a slightly larger separation hardly evaporate, as shown in our Figures 5 and 12. This is due to the runaway property of the mass-loss evolution discussed in this study. We calculated the evolution of a Jupiter mass planet with a 15 M_{Earth} core at 0.025 AU (not shown as a figure), which is the same as Figure 2 of Owen & Wu (2013). The planet lost only 1.6% of its total mass (~5 M_{Earth}) after 10 Gyr, which is
three times larger than the result of Owen & Wu (2013) and does not differ by an order of magnitude. The slight difference of the lost mass is caused by different mass-loss models. We used a semianalytical model including recombination-limited escape, which corresponds to the “EUV-driven” regime in Owen & Wu (2013). Owen & Wu (2013) used the rate of mass loss obtained by their hydrodynamic simulation and the mass loss is mainly in the “X-ray-driven” regime. The difference of XUV models also affects the results. The difference from Lopez & Fortney (2013) is due to the higher-core mass (64 $M_{\text{Earth}}$) of their 320 $M_{\text{Earth}}$ planet, as well as their large separation. The core mass strongly affects the mass-loss evolution, as shown in our Figures 9 and 11.

4.2. Validity of the Model

We calculated the XUV radius $R_{\text{XUV}}$ by assuming a pressure of 1 nbar as a crude estimate. The pressure at the ionization front (which is identical to the XUV radius) can be obtained in the framework of our semianalytical model by using our Equations (8) and (9) (Figure 14). The pressure at the ionization front increases as a function of XUV flux and becomes ~10 nbar at higher XUV levels. This increase in the pressure (namely, the increase in the number density) can be found in Murray-Clay et al. (2009) and Owen & Jackson (2012). We evaluate the error caused by our assumption for the pressure at the XUV radius in Figure 15. The amount of mass loss changes only a few percent when we artificially change the pressure at $R_{\text{XUV}}$. Mass loss is more affected by the presence of the radiation-recombination-limited escape. The rate of mass loss in the radiation-recombination-limited regime is enhanced by the tidal effect, but the amount of mass loss is reduced compared with that obtained without the radiation-recombination-limited regime (the energy-limited regime only).

Pre-main sequence (PMS) stars initially have radii $\sim$3 times larger than the solar radius (the case of 1 solar mass; Palla & Stahler 1993), which corresponds to $\sim$0.014 AU, and shrink with time to evolve into main sequence (MS) stars. The innermost cases of observed planets and our model (0.015 AU; Figure 12) are close to being inside the radii of early PMS stars. Planets at this innermost orbit might be engulfed at the early PMS stage. The observed innermost planets are possibly migrated after the stage. Because the survival masses of the migrated planets are almost the same as those of the planets formed in situ (Figure 11), the planet engulfment and migration do not change our discussion of planet evaporation.

Inner cavities of protoplanetary disks occur at $\sim$0.03–0.04 AU (Najita et al. 2007 and references therein). Planets that migrated inside the cavity are irradiated by stellar XUV radiation at the PMS stage before dissipation of the protoplanetary disks. Observations show that the X-ray luminosities of PMS stars are $\sim$10^{30} erg s^{-1} on average (Güdel et al. 2007), which are similar to MS stars in the saturation phase (Jackson et al. 2012). If the X-ray luminosity scales with the bolometric luminosity, as suggested by observations (Güdel et al. 2007), early PMS stars, with bolometric luminosities a few times larger than MS stars within a few million years (Palla & Stahler 1993), might have X-ray luminosities a few times larger. Assuming the same dependence for XUV luminosity, our model, which assumed that the mass loss starts after the disk dissipation, provides the minimum estimate for the survival mass. Because the cumulative XUV energy in the neglected 10^7 yr is smaller than the XUV energy in the saturation phase (10^8 yr), however, the effect would be small.

4.3. Effects of Uncertainties

Stellar X-ray luminosities vary by an order of magnitude, even among similarly aged stars in a cluster (Jackson et al. 2012). Although difficult to ascertain by observations, the stellar extreme ultraviolet luminosity is expected to be similarly diverse (Sanz-Forcada et al. 2011). In addition, the efficiency of thermal atmospheric escape is uncertain by a factor of $\sim$3 (Leitzinger et al. 2011; Lopez et al. 2012). To elucidate the effects of such diversity and uncertainty on our results, we plot the minimum survival masses as functions of semi-major axis for arbitrarily altered rates of mass loss (see Figure 16). These results show an insensitivity to the assumed mass-loss rates compared with that expected only from changes to compensate the mass-loss rates for XUV flux. This insensitivity arises from the effect of stellar irradiation on planetary radius and partially from tidal effects on mass-loss rates. The minimum survival masses obtained by suppressing and accelerating the mass loss are compared with the observed exoplanets distribution in Figure 17. Comparing Figures 12 and 17, we observed that varying the rate of mass loss exerts a smaller effect than that exerted by varying the core mass.
The sub-Jupiter desert is best fit by our fiducial model (defined in previous sections). The reduced model partially reproduces the desert, but its survival masses are located below the upper boundary of the desert. Therefore, mass-loss processes require thermal atmospheric escape to produce the observed desert patterns.

### 4.4. Implications for Planet Formation Theory

To gain insights into planetary formation, we compared the results of planetary formation models with observations. Population syntheses of planetary formation have been previously researched, for example, in a series of papers by Ida & Lin and Mordasini et al. According to these studies, planets of sub-Jupiter mass are scarce at $\lesssim 1$ AU because Jupiter-like planets form at large distances ($>1$ AU) from their host star and migrate inward. These results are inconsistent with the observed planet populations, in which no desert exists at $\lesssim 1$ AU (Howard et al. 2010, 2012). As discussed earlier, the observed sub-Jupiter desert is compacted into $\lesssim 0.04$ AU. Thus, another mechanism must be responsible for the observed desert. As we have shown, the desert is consistent with evaporation of the envelopes of sub-Jupiter planets orbiting close to their host star. Another likely mechanism, proposed by Benítez-Llambay et al. (2011), is planetary migration and trapping near the inner edge of the disk. Calculating the interaction between the planet and the disk gas, they showed that this mechanism reproduces the mass–period distribution of inner-orbit exoplanets $<0.04$ AU. In their calculation, smaller migratory planets are trapped at the inner edge, while heavier planets penetrate the inner edge and are trapped at the orbit whose mean motion resonates at 2:1 with the inner edge. The critical mass is $\sim 1$ Jupiter. However, this mechanism predicts a desert of both sub-Jupiters and super Earths. In real planetary populations, many super Earths compatible with hot Jupiters orbit their host stars within 0.04 AU (Howard et al. 2012). A third possible mechanism is that most closely orbiting ($<0.04$ AU) exoplanets result from tidal trapping of planets with eccentric orbits. Beaugé & Nesvorny (2013) proposed that inefficient trapping of smaller planets can explain the observed desert because the gas-poor composition of such planets precludes efficient dynamical tides. This scenario has yet to be numerically tested, but is expected to also predict a desert of closely orbiting super Earths, even if it successfully reproduces
the desert of sub-Jupiters. Therefore, neither of these alternative mechanisms can directly explain why the sub-Jupiter desert coexists with an abundance of closely orbiting super Earths. One possible solution is that a fraction of inwardly migrating planets halts at $\lesssim 0.04$ AU, possibly in the inner cavity of the protoplanetary disk, during planetary formation. Following formation and migration, their envelopes evaporate to create the desert of sub-Jupiters.

To produce the sub-Jupiter desert by evaporation processes, constraints must be placed on the planetary formation scenario. As discussed above, hot Jupiters with large cores ($\gtrsim 20 - 30 M_{\text{Earth}}$) largely retain their envelopes. The model is consistent with observation if a core mass of $10 M_{\text{Earth}}$ is assumed (Figure 12). Thus, our results suggest that the cores of hot Jupiters are typically small. This scenario requires efficient gas accretion onto the core during planet formation. The migration history of interactions with disk gas exerts a minor influence on our results; hence, the migration of hot Jupiter by interactions with disk gas is not apparently constrained. However, if interplanetary interactions induce the migration of multiple sub-Jupiters after $\sim 0.1 - 1$ Gyr, these planets should be detected in the desert because they would have received no intense XUV radiation from their host stars during their youth. This implies that the population of inner exoplanets is not dominated by such later-migrating planets. In the radius distribution of likely Kepler planets, the number of super Earths exceeds that of hot Jupiters by 30 times at $\lesssim 0.25$ AU; however, the subpopulations are approximately equal at $\lesssim 0.04$ AU (Howard et al. 2012). A fraction of these super Earths might be remnants of evaporated hot Jupiters. Super Earths occupy multiple-planet systems at a higher ratio (relative to single planet systems) than hot Jupiters (see Beaugé & Nesvorny 2013). Thus, the fraction of evaporated remnants might be higher for super Earths occupying single-planet systems than those occupying multiple systems.

5. SUMMARY AND CONCLUSIONS

The exoplanet population is characterized by a desert of sub-Jupiter planets at $\lesssim 0.04$ AU. We developed a numerical model that calculates the mass loss and thermal evolution of planets, accounting for XUV-driven thermal atmospheric escape. Atmosphere is lost by both energy-limited escape and radiation-recombination-limited escape. Further loss occurs via the Roche-lobe overflow that is induced by and follows atmospheric escape. We showed that the runaway property of the mass loss leads to a dichotomous population in which heavier planets remain as hot Jupiters, while smaller planets completely evaporate, leaving naked cores. The results strongly depend on the core mass and weakly depend on migration history. The observed sub-Jupiter desert in both mass and radius distributions was successfully reproduced by modeling the evaporation of sub-Jupiters with small cores ($10 M_{\text{Earth}}$). Comparing our results with other possible explanations for the desert and considering the abundance of inner-orbit super Earths, we conclude that evaporation most likely explains the sub-Jupiter desert.

The authors acknowledge Tristan Guillot for fruitful discussions and the referee for comments that improved the draft. This work is supported by Global COE program “From the Earth to Earths” and Grants-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan (23244027 and 24340102).

REFERENCES

Baraffe, I., Selsis, F., Chabrier, G., et al. 2004, A&A, 419, L13
Beaugé, C., & Nesvorny, D. 2013, ApJ, 763, 12
Benítez-Llambay, P., Massef, F., & Beaugé, C. 2011, A&A, 528, A2
Freedman, R. S., Marley, M. S., & Lodders, K. 2008, ApJS, 174, 504
Gu, P.-G., Liu, D. N. C., & Bodenheimer, P. H. 2003, ApJL, 588, 509
Güdel, M., Briggs, K. R., Arzner, K., et al. 2007, A&A, 468, 353
Guo, J. H. 2011, ApJ, 733, 98
Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, ApJL, 553, L153
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15
Howard, A. W., Marcy, G. W., Johnson, J. A., et al. 2010, Sci, 330, 653
Hubbard, W. B., Hattori, M. F., Burrows, A., Habeny, I., & Sudarsky, D. 2007, Icar, 187, 358
Ida, S., & Lin, D. N. C. 2008, ApJ, 673, 487
Jackson, A. P., Davis, T. A., & Wheatley, P. J. 2012, MNRAS, 422, 2024
Jackson, B., Miller, N., Barnes, R., et al. 2010, MNRAS, 407, 910
Kurokawa, H., & Kaltenegger, L. 2013, MNRAS, 433, 3239
Lammer, H., Selsis, F., Ribas, I., et al. 2003, ApJL, 598, L121
Leitzinger, M., Odert, P., Kuliok, Y. N., et al. 2011, P&SS, 59, 1472
Lopez, E. D., & Fortney, J. J. 2013, ApJ, 776, 2
Lopez, E. D., Fortney, J. J., & Miller, N. 2012, ApJ, 761, 59
Marley, M. S., Fortney, J. J., Hubickyj, O., Bodenheimer, P., & Lissauer, J. J. 2007, ApJL, 655, 541
Mazeh, T., Zucker, S., & Pont, F. 2005, MNRAS, 356, 955
Mordasini, C., Alibert, Y., Benz, W., & Naef, D. 2009, A&A, 501, 1161
Mordasini, C., Alibert, Y., Georgy, C., et al. 2012, A&A, 547, A112
Murray-Clay, R. A., Chiang, E. I., & Murray, N. 2009, ApJ, 693, 23
Najita, J. R., Carr, J. S., Glassgold, A. E., & Valenti, J. A. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 507
Nayakshin, S., & Lodato, G. 2012, MNRAS, 426, 70
Owen, J. E., & Jackson, A. P. 2012, MNRAS, 425, 2931
Owen, J. E., & Wu, Y. 2013, ApJ, 775, 105
Palla, F., & Stahler, S. W. 1993, ApJL, 418, 414
Ribas, I., Guinan, E. F., Güdel, M., & Audard, M. 2005, ApJ, 622, 680
Sanz-Forcadar, J., Micela, G., Ribas, I., et al. 2011, A&A, 532, A6
Saumon, D., Chabrier, G., & van Horn, H. M. 1995, ApJS, 99, 713
Southworth, J., Wheatley, P. J., & Samus, G. 2007, MNRAS, 379, L11
Szabó, G. M., & Kiss, L. L. 2011, ApJL, 727, L44
Trilling, D. E., Benz, W., Guillot, T., et al. 1998, ApJ, 500, 428
Valencia, D., Ikoma, M., Guillot, T., & Nettelmann, N. 2010, A&A, 516, A20
Vinet, P., Rose, J. H., Ferrante, J., & Smith, J. R. 1989, JPCM, 1, 1941
Wagner, F. W., Sohl, F., Hussmann, H., Grott, M., & Rauer, H. 2011, Icar, 214, 366
Watson, A. J., Donahue, T. M., & Walker, J. C. G. 1981, Icar, 48, 150
Weiss, L. M., Marcy, G. W., Rowe, J. F., et al. 2013, ApJ, 768, 14
Wu, Y., & Lithwick, Y. 2013, ApJL, 772, 74
Yukutake, T. 2000, PEPJ, 121, 103