Mass-Loss Evolution of Exoplanets: Effects on population and Composition

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Abstract

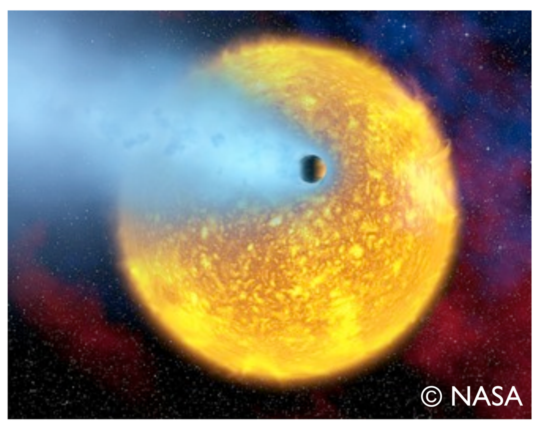
Purpose: To figure out effects of mass-loss on population and composition of exoplanets

Method: To calculate thermal evolution and mass-loss evolution, considering thermal atmospheric escape and Roche-lobe over flow

Results: Mass-loss creates a Sub-Jupiter desert at < 0.04 AU, which is consistent with observation. Observed trend of composition of Super-Earths can be explained by mass-loss

1. Introduction

Mass-loss of exoplanets



HD 209458 b (1.13 $M_{Jupiter}$, 0.045AU)
- hydrogen (Vidal-Madjar et al., 2003)
- carbon, oxygen (Vidal-Madjar et al., 2004; Ben-Jaffel and Sona Hosseini, 2010)
- silicon (Linsky et al., 2010)

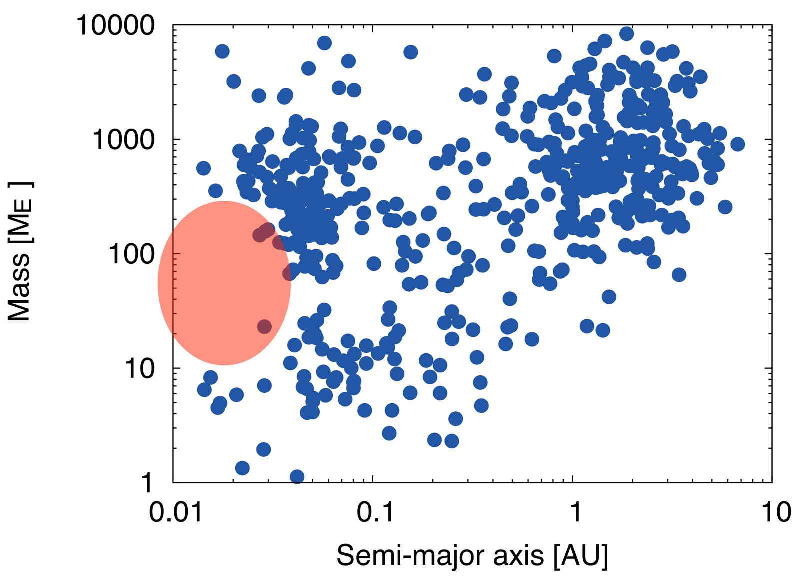
HD 189733 b (0.8 $M_{Jupiter}$, 0.031AU)
- hydrogen (Lecavelier Des Etangs et al., 2010)

WASP 12 b (1.41 $M_{Jupiter}$, 0.023AU)
- metals (Fosseti et al., 2010)

55 Cancri b (0.8 $M_{Jupiter}$, 0.115AU)
- hydrogen (Ehrenreich et al., 2012)

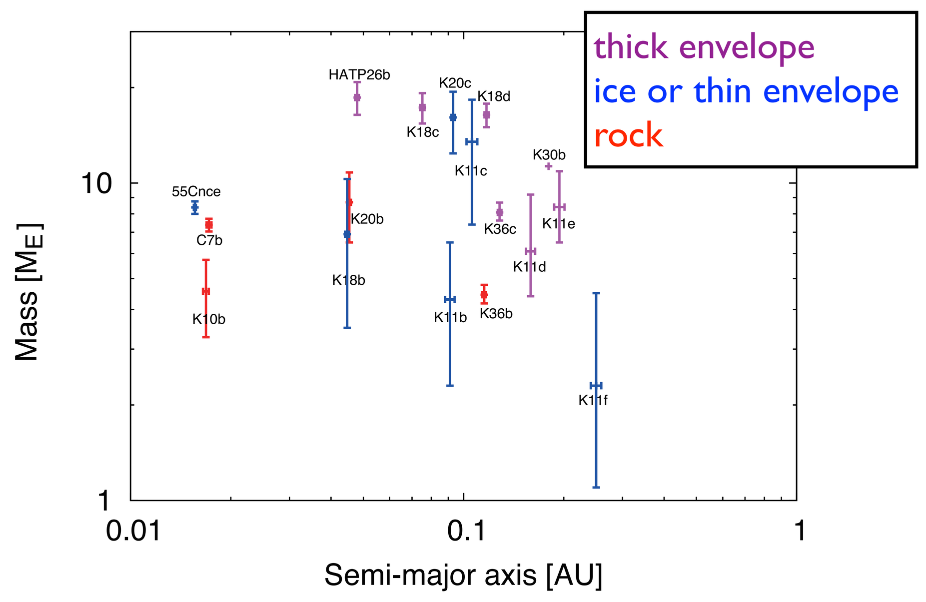
Theoretical studies have shown that the mass-loss is possibly induced by XUV (X-ray + EUV) heating of upper atmosphere (e.g., Murray-Clay et al., 2009)

Population of Hot-Jupiters



Sub-Jupiter desert at close-in orbits

Composition of Super-Earths



Gas-rich Super-Earths have larger masses and far orbits

We calculate evolution of planets with mass-loss and thermal cooling and show effects of mass-loss on population and composition

2. Model

Structure calculation

Mass conservation

$$\frac{d\ln r}{dM_r} = -\frac{1}{4\pi r^3 \rho}$$

Hydrostatic

$$\frac{d\ln p}{dM_r} = -\frac{GM_r}{4\pi r^4 p}$$

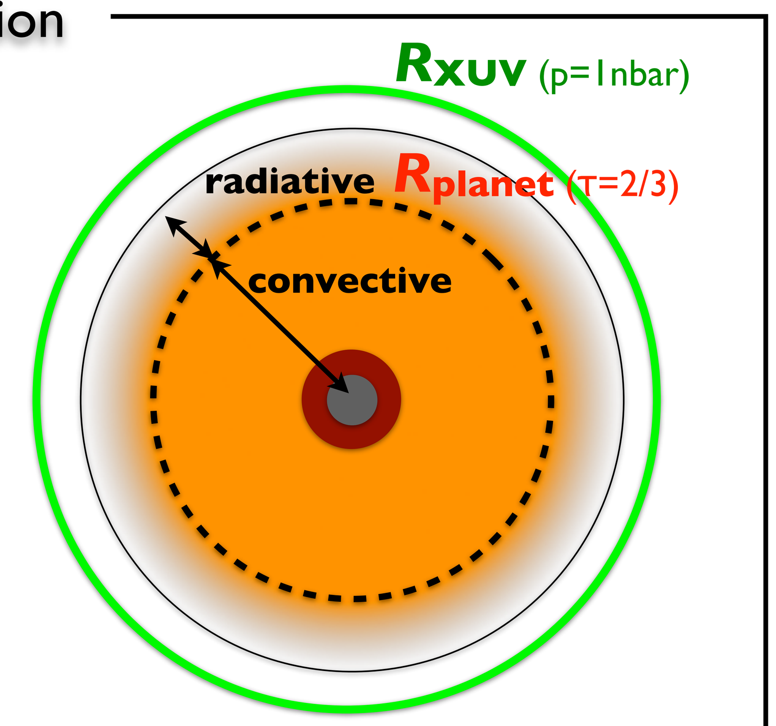
Radiative equilibrium or convective

τ< 2/3 : isothermal (Guillot, 2010)

$$T^4 = \frac{3T_{int}^4}{4}\left(\frac{2}{3}+\tau\right) + \frac{3T_{irr}^4}{4} f\left(\frac{2}{3} + \frac{1}{\gamma\sqrt{3}} + \left(\frac{\gamma}{\sqrt{3}} - \frac{1}{\gamma\sqrt{3}}\right)e^{-\gamma\tau\sqrt{3}}\right)$$

$$\frac{dT}{dr} = -\frac{3\kappa\rho}{16\sigma_{SB}T^3}\frac{L_{int}}{4\pi r^2}$$

$$\frac{d\ln T}{dM_r} = -\frac{GM_r}{4\pi r^4 p}\left(\frac{\partial \ln T}{\partial \ln p}\right)_s$$



Equation of state
- H/He - Saumon et al. (1995)
- rock / iron - generalized Ryberg EOS, Wagner et al. (2011)

Evolution calculation

Thermal evolution

$$\int_{M_{core}}^{M_p} T\frac{dS}{dt}dM_r + C_p\frac{dT_{core}}{dt} = 4\pi R_p^2 \sigma T_{int}^4 - L_{radio}$$

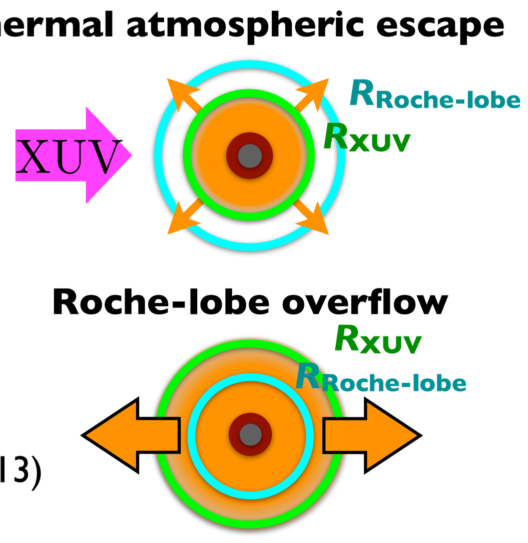
Mass-loss evolution

$R_{Roche-lobe} > R_{XUV}$ **thermal atmospheric escape**

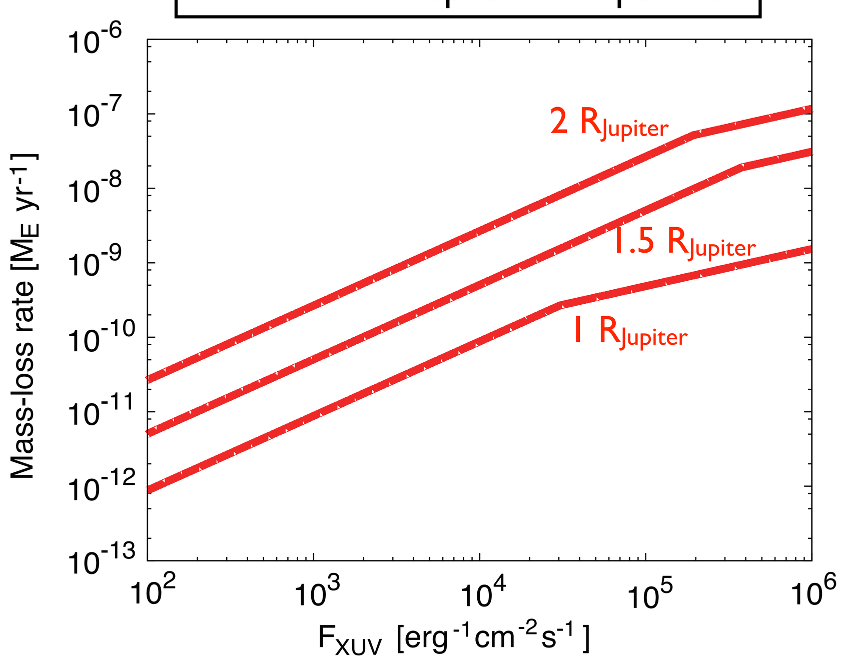
Semi-analytical model based on Murray-Clay et al. (2009)

$R_{Roche-lobe} < R_{XUV}$ **Roche-lobe Overflow**

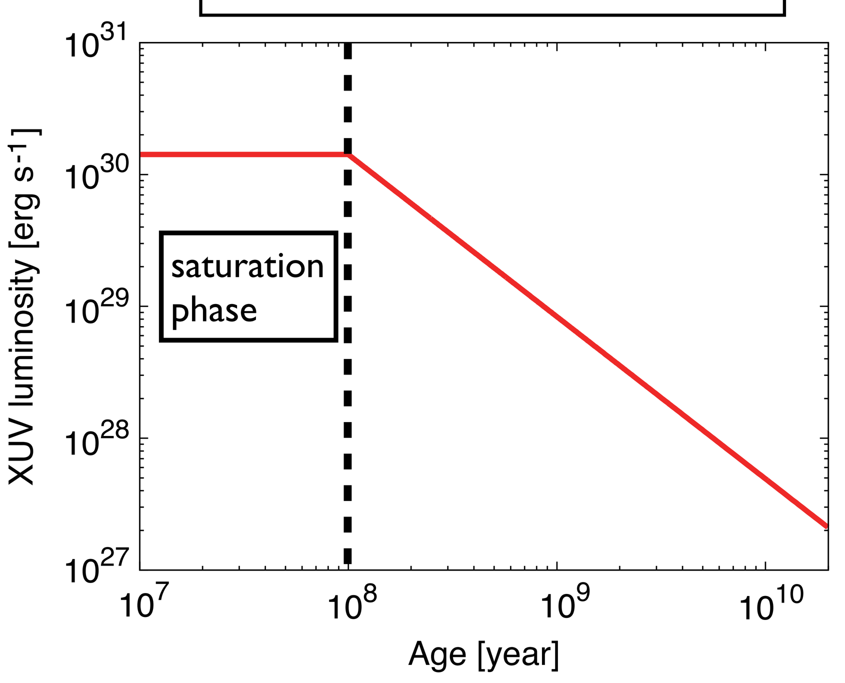
Envelope is lost until $R_{XUV} = R_{roche-lobe}$ (Kurokawa and Kaltenegger, 2013)



Thermal atmospheric escape rate

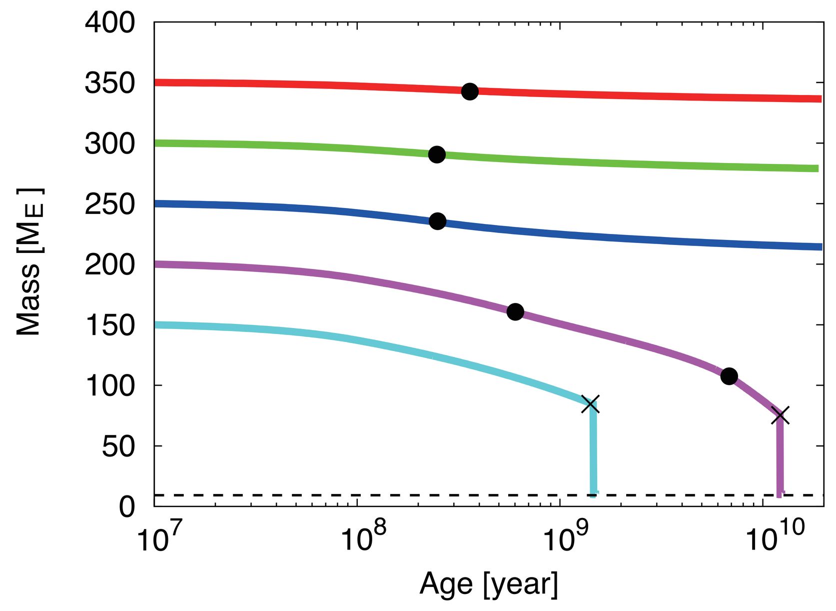


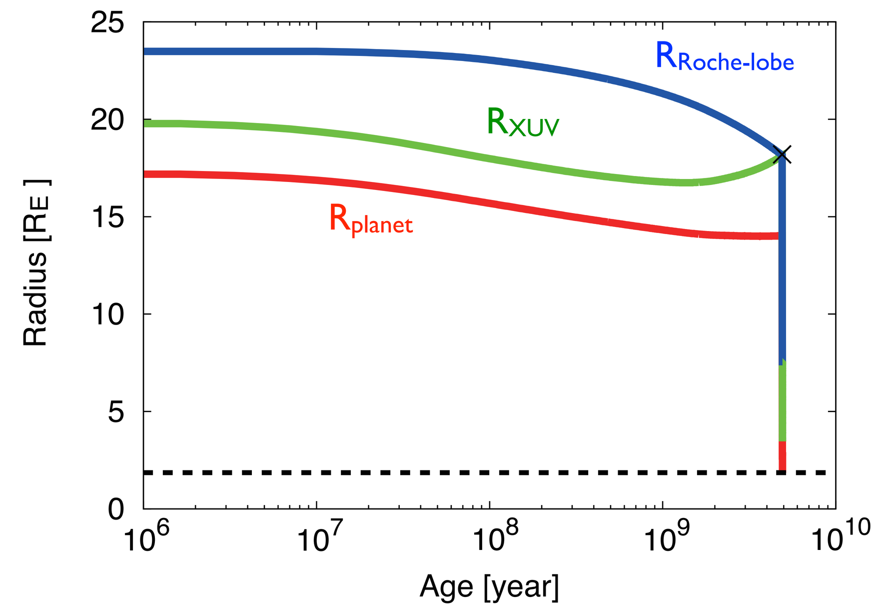
Stellar XUV model



3. Results

Example of mass-loss evolution



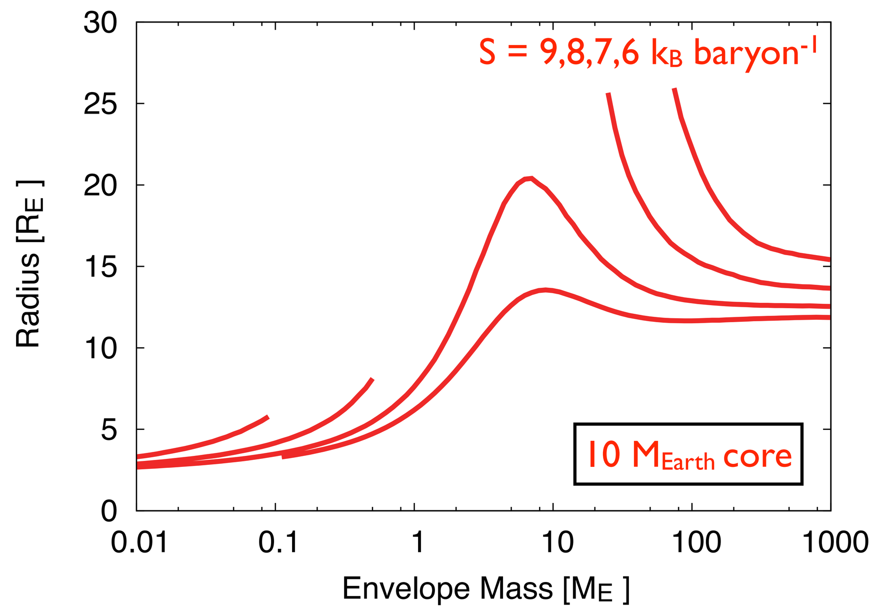


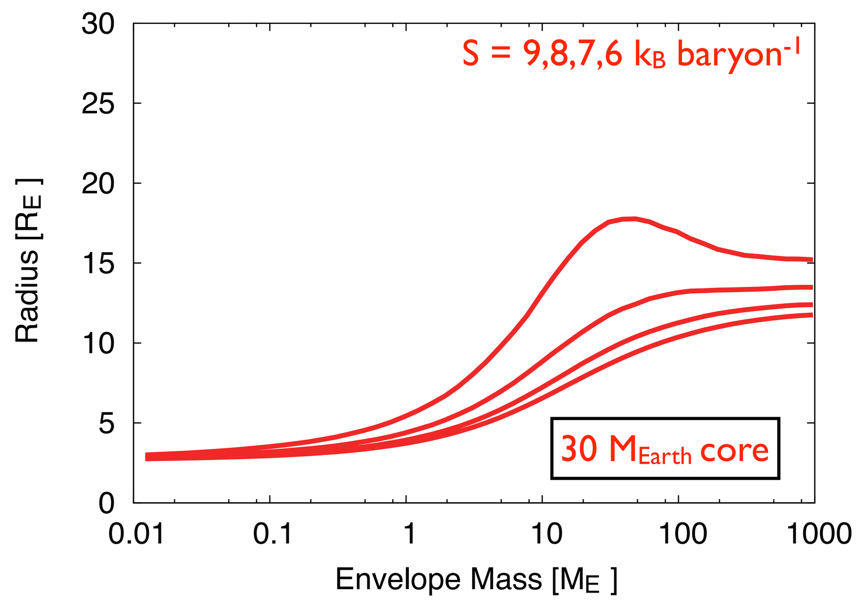
(left) Evolution of mass of planets having 10 M_{Earth} core at 0.02 AU, circles denote when thermal escape regime changes and crosses denote when Roche-lobe overflow occurs

(right) Evolution of radius in the case of complete evaporation

- Mass -loss results in a dichotomy: complete evaporation or remaining almost all envelope
- Mass-loss is followed by expansion of the planet and Roche-lobe overflow

Envelope mass - radius relation

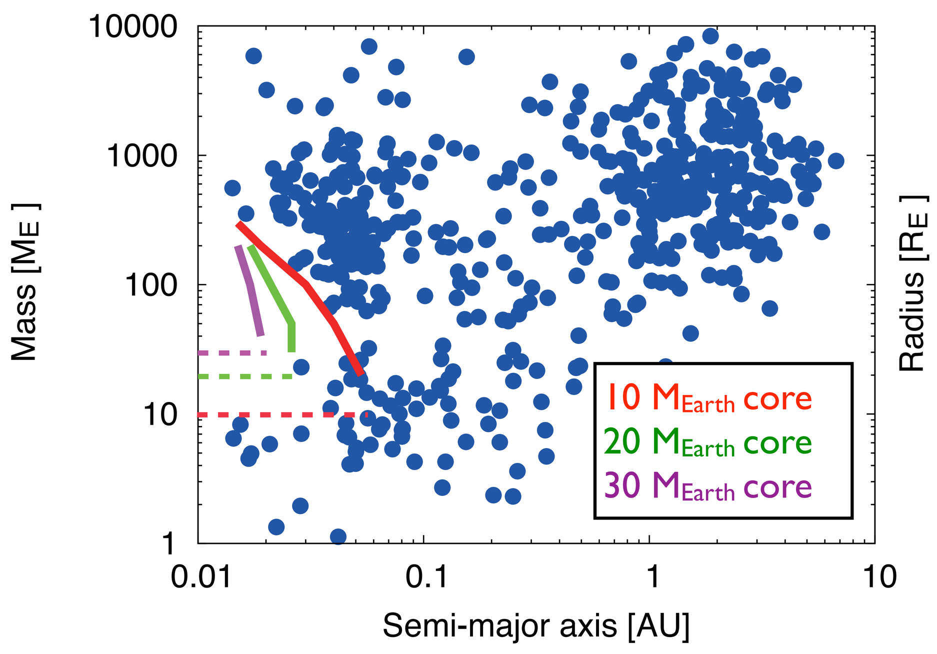


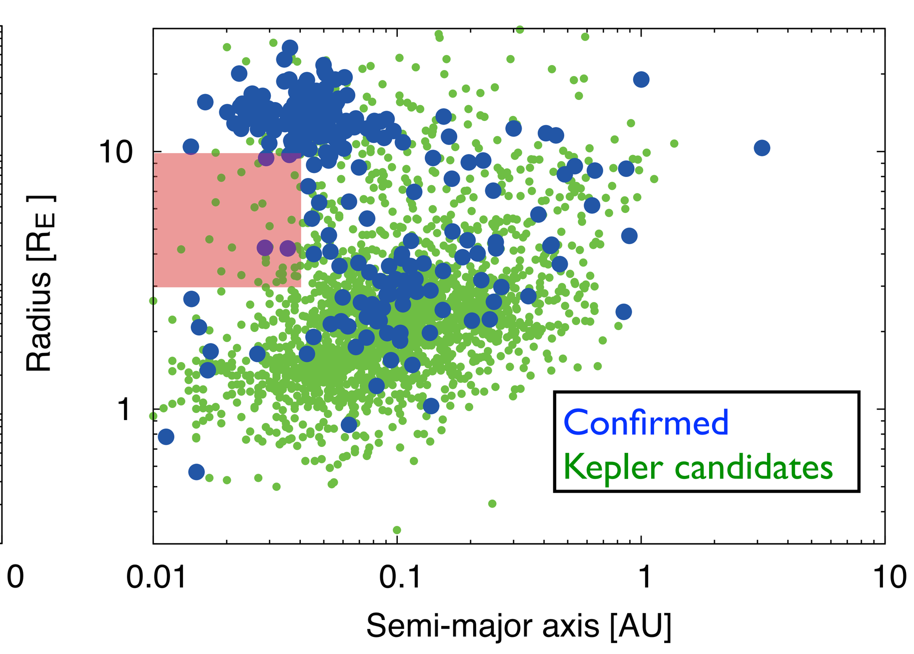


Envelope mass - radius relation of 10 M_{Earth} core planets (left) and 20 M_{Earth} core planets (right) at 0.015 AU

- Mass-loss is followed by expansion of the planet in Jupiter-mass regime = mass-loss is RUNAWAY
- The radius below 100 M_{Earth} is strongly depends on core mass

Evaporation of Hot-Jupiters



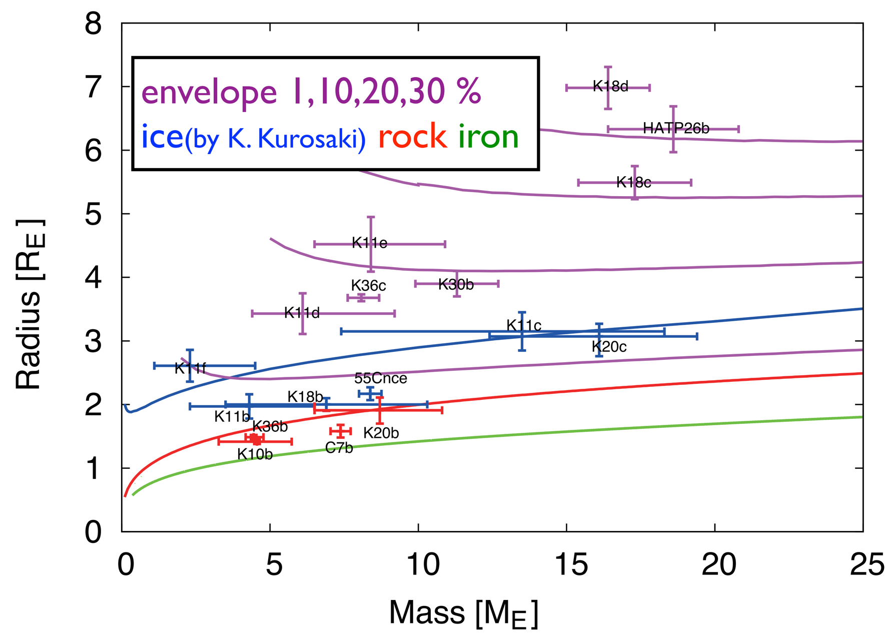


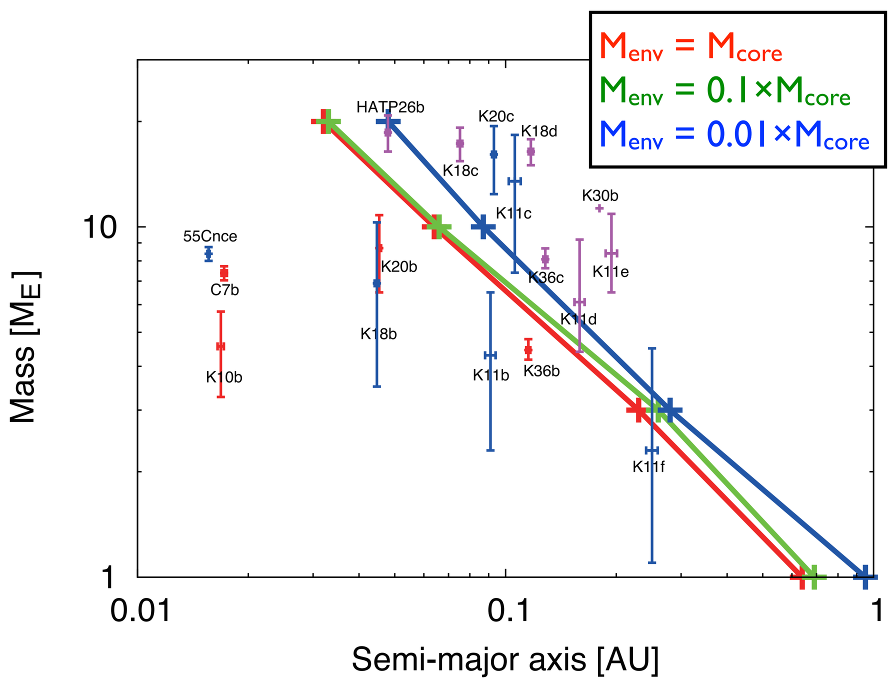
(left) Observed mass population and calculated mass for complete evaporation in 10 Gyr

(right) Observed radius population of confirmed planets and Kepler planet candidates

- Sub-Jupiter desert in mass population can be created by mass-loss if Hot-Jupiters have small cores (10 M_{Earth})
- Sub-Jupiter desert in radius population is also consistent with the mass-loss

Composition of Super-Earths





(left) Observed Super-Earths and theoretical mass-radius relation at 0.1 AU

(right) Observed Super-Earths and calculated orbital radius for complete evaporation of envelope in 10 Gyr

- All Super-Earths having thick envelopes are farther than the critical orbital radius
- Super-Earths closer than the critical orbital radius can be interpreted as rocky or icy bodies without envelope

4. Discussion

Results of Hot-Jupiters suggest that Hot-Jupiters tend to have small cores of 10 M_{Earth}
- Efficient gas capture in formation phase
- Later migration in $10^{8\text{-}9}$ year should be minor process to create Sub-Jupiter desert by evaporation

Results of Super-Earths suggest that the trend of composition is created by mass-loss
- Almost all Super-Earths once captured envelopes and lost the envelopes after formation
- Super-Earths inside the critical orbital radius having moderate radii sould be icy bodies, which indicates migration after formation