Effects of Atmospheric Escape on Planetary Evolution

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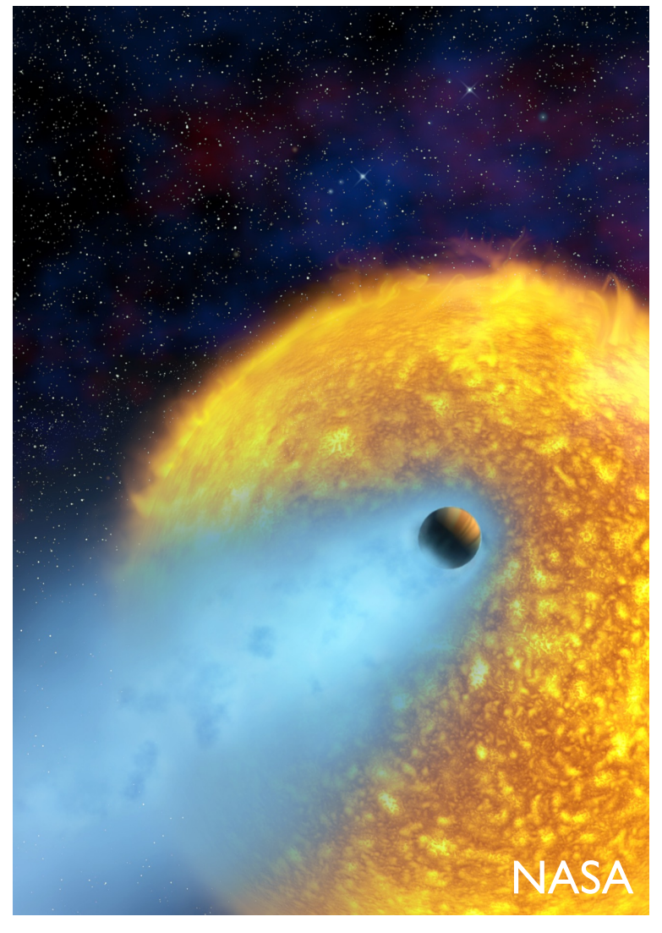
Background

- Intense EUV radiation drives hydrodynamic escape of close-in exoplanets by photoionization heating of hydrogen atoms
- The mass-loss rate and the efficiency depend on the EUV flux from the host star (Murray-clay et al. 2009)
  - Energy-limited: low EUV flux, the mass-loss rate is almost proportional to the EUV flux
  - Recombination-limited: high EUV flux, EUV input energy is lost to the radiative recombination and the efficiency is lower than energy-limited value

Aim of the study

- Atmospheric escape changes the evolution of close-in planets
- Classical planetary evolution models assumed the energy-limited mass-loss rates

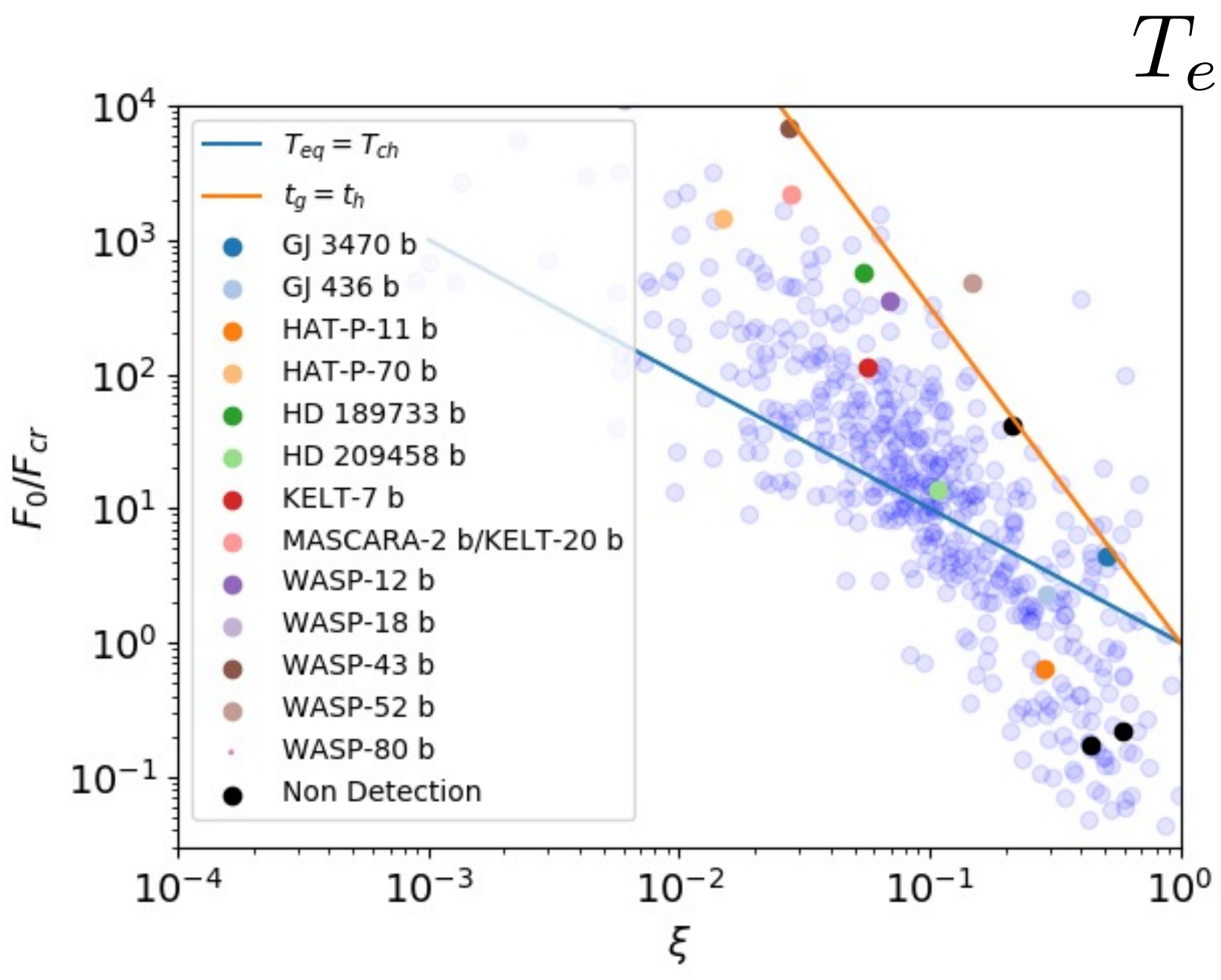


- To assess the effect of the evolution of the atmospheric escape process (energy-limited or recombination-limited) on the planetary evolution

Relevant Temperatures and Timescales

- Gravity, photoheating, and gas expansion determine the physics of the system
- We can define relevant temperatures and timescales
  - Equilibrium temperature from photoionization balance: $T_{eq} \sim 10^4\ \mathrm{K}$
  - Characteristic temperature which characterizes the photoheating speed to gas expansion: $kT_{ch} = \dfrac{\Gamma}{c_p/\mu m_{\mathrm{H}}} \dfrac{R_p}{c_{ch}}$
  - The ratio between the characteristic temperature and the equilibrium temperature $\dfrac{T_{ch}}{T_{eq}} = \left(\dfrac{R_p \Gamma}{c_{eq}^3 c_p}\right) \sim \left(\dfrac{R_p}{R_g}\right)^{2/3} \left(\dfrac{F_{EUV}}{F_{cr}}\right)^{2/3}$
  - Gravitational and photoheating timescale:

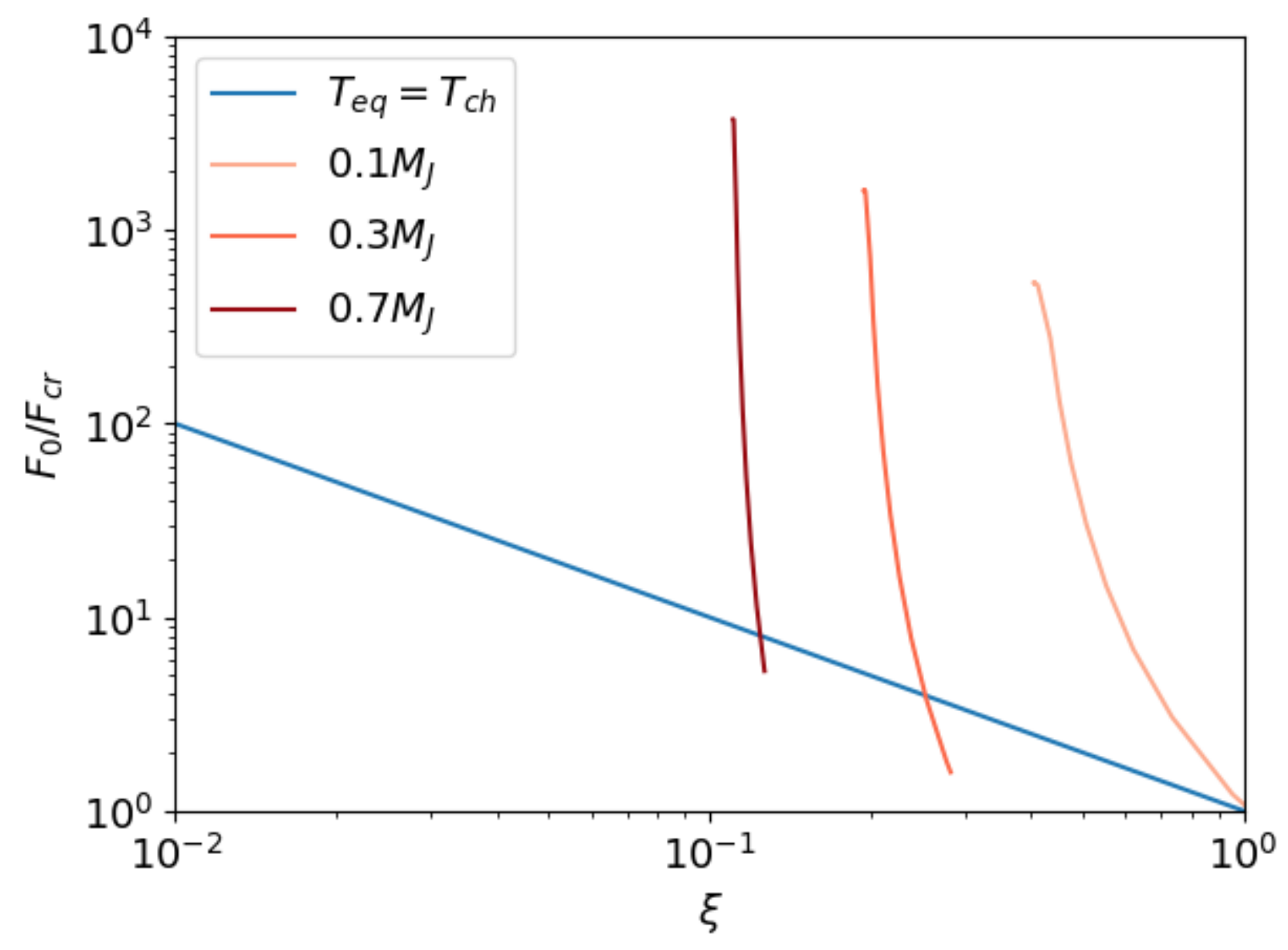
$$t_g = \sqrt{\frac{R_p^3}{GM_p}} \qquad t_h = \frac{R_p}{c_{ch}} \qquad \frac{t_g}{t_h} \sim \left(\frac{R_p}{R_g}\right)^{5/6} \left(\frac{F_{EUV}}{F_{cr}}\right)^{1/3}$$



EUV flux exceeds the critical flux in many exoplanets with detection of hydrogen atom

Evolution of planets with atmospheric escape

Planeary Evolution in ξ-F_{EUV}/F_0 Plane

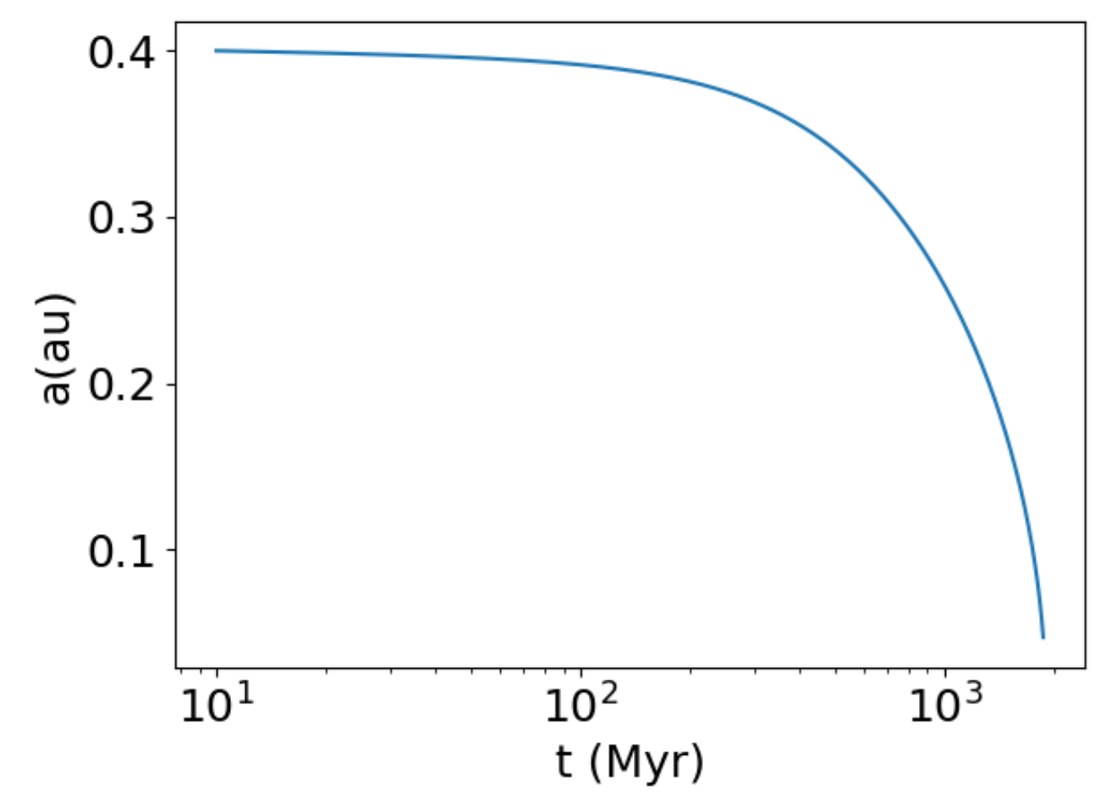


Without orbital migration

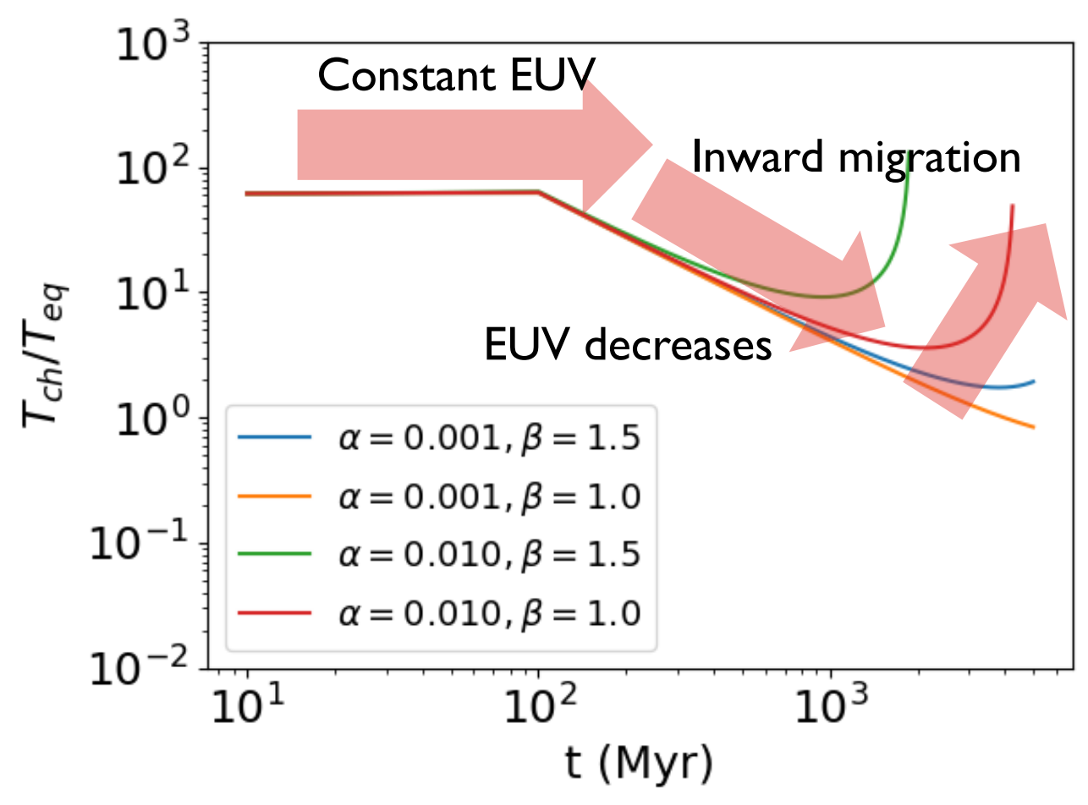
EUV luminosity depends on the stellar age
The system reaches energy-limited in Gyr
In the case of typical hot Jupites, the effect of mass evolution is not significant

Escaping atmosphere may form torus around the host star (Kurbatov et al. 2022)
Interaction between torus and planet causes the inward migration

Orbital Evolution with atmospheric escape

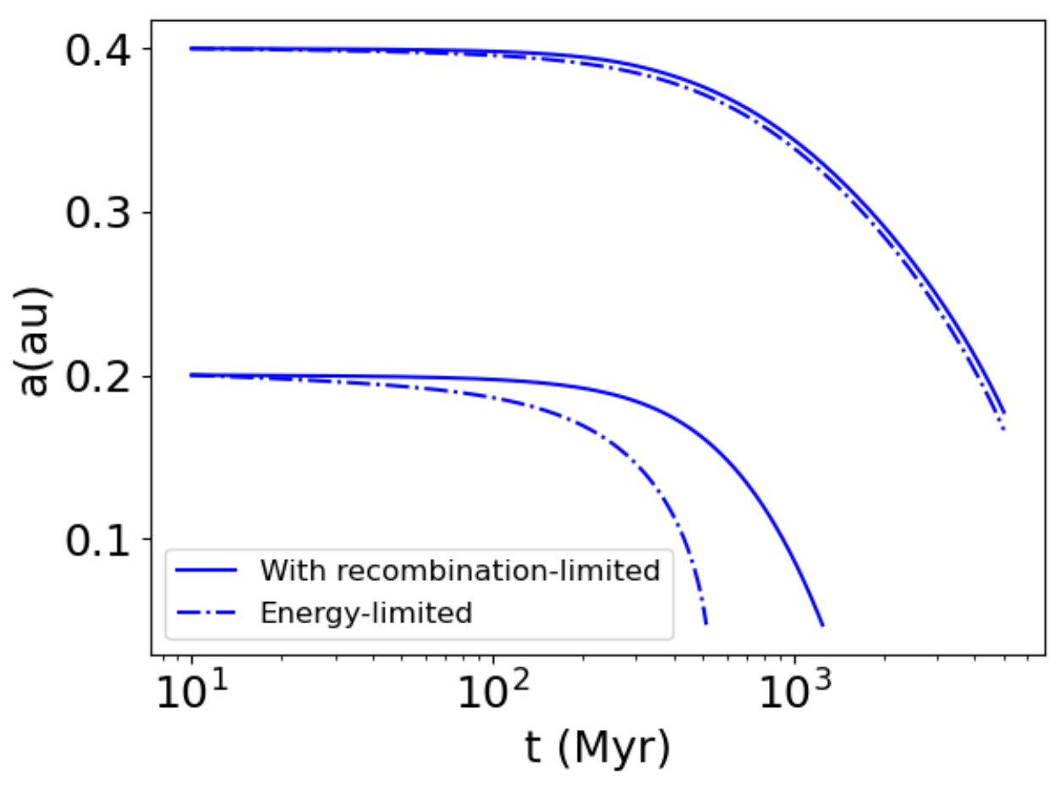


Evolution with different viscous parameters



If the migration speed is enough high, the planets reaches the recombination-limited again

Orbital Evolution considering the mass-loss regime evolution with different initial semi-major axis



The mass-loss efficiency may have impact on the orbital evolution due to the torus because the mass-loss rate changes the tidal effect
The low efficiency of recombination-limited reduces the migration speed by factor of 2

Conclusions

- The physics of EUV driven atmospheric escape can be understood by relevant timescales and temperatures
- As the stellar EUV flux decreases, the mass-loss regime changes from the recombination-limited to energy-limited
- If we consider the migration due to the torus formed by the atmospheric escaping gas, the system turns out to be recombination-limited again after the system reaches the energy-limited
- The migration speed depends on the mass-loss rate and the mass-loss regime changes the orbital evolution by a factor of 2