FORMATION OF MULTIPLE TERRESTRIAL PLANETS UNDER THE INFLUENCE OF A HOT JUPITER

2H004

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ABSTRACT

Context. According to the hybrid scenario of planet formation (Inutsuka 2009), giant planets can initially form via gravitational instability in a protoplanetary disk, and subsequently terrestrial planets grow on the basis of the core accretion model.

Methods. In this work, we investigate formation of close-in terrestrial planets from planetary embryos under the influence of a hot Jupiter (HJ) using gravitational *N*-body simulations that include gravitational interactions between the gas disk and the planet (e.g., type I migration).

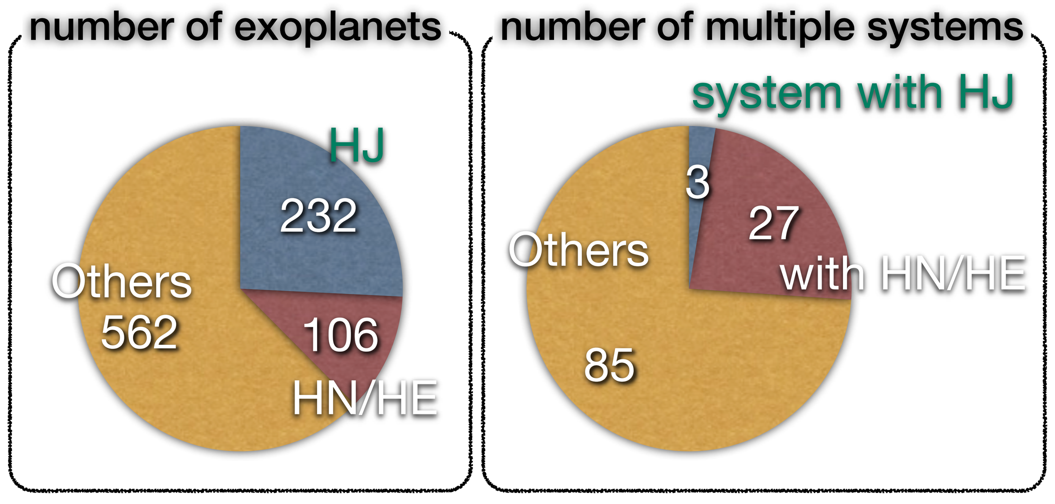
Results. We find that several planets are formed and captured in mutual mean motion resonances outside the edge of the gap in the disk, which is opened up by the HJ. The innermost planet is also in the 2:1 resonance with the HJ and thus gravitationally interact with each other, leading to inward migration of the HJ. The migration timescale of the HJ depends on the solid amount in the disk; the HJ does not exhibit inward migration in the result of decreased solid density. We can give several possible explanations for the origin of properties of observed close-in exoplanet systems; we propose two possibilities for the lack of companion planets in HJ systems.

1. BACKGROUND

1.1 Lack of additional planets in hot Jupiter (HJ) systems

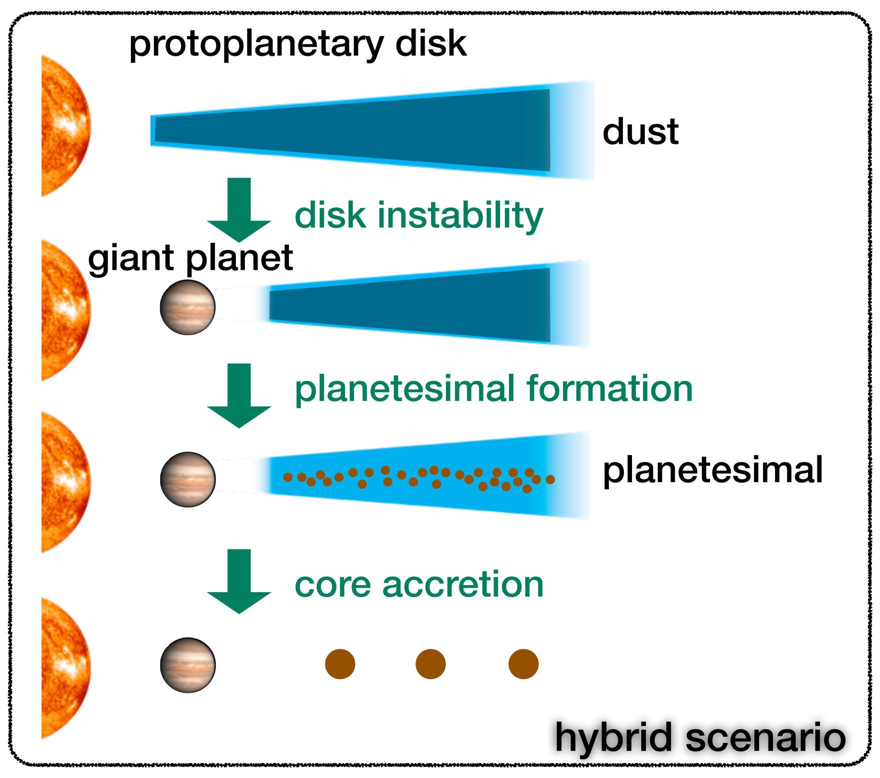
Observations suggest that there is a lack of observed planets in HJ systems (e.g., Latham et al. 2011; Steffen et al. 2012).

Observational data (exoplanet.eu)



About 25% of exoplanets are HJs, however, only 2% or less of multiple systems include HJs. In particular, this tendency is remarkable in close-in systems, where more than one planet resides in close-in orbits.

1.2 Hybrid scenario of planet formation (Inutsuka 2009)



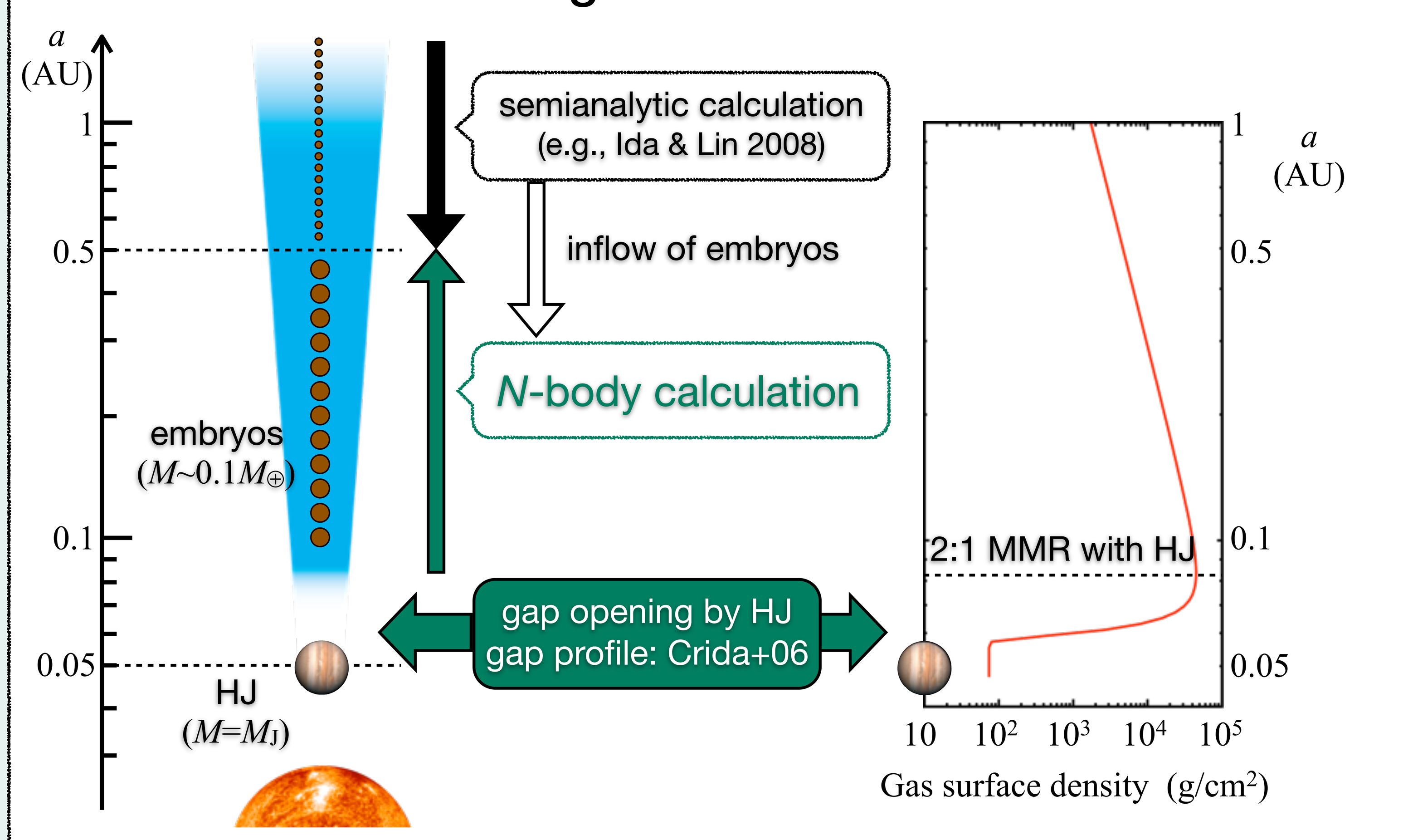
Inutsuka (2009) proposed "hybrid scenario" of planet formation, where giant planets form via gravitational instability before the onset of the core accretion stage. Therefore, formation of terrestrial planets can occur under the influence of the giant planets.

2. THIS WORK

2.1 Aim

We investigate formation of close-in terrestrial planets under the influence of a giant planet (HJ) using gravitational *N*-body simulations that include tidal interaction with the gas disk.

2.2 Numerical modeling



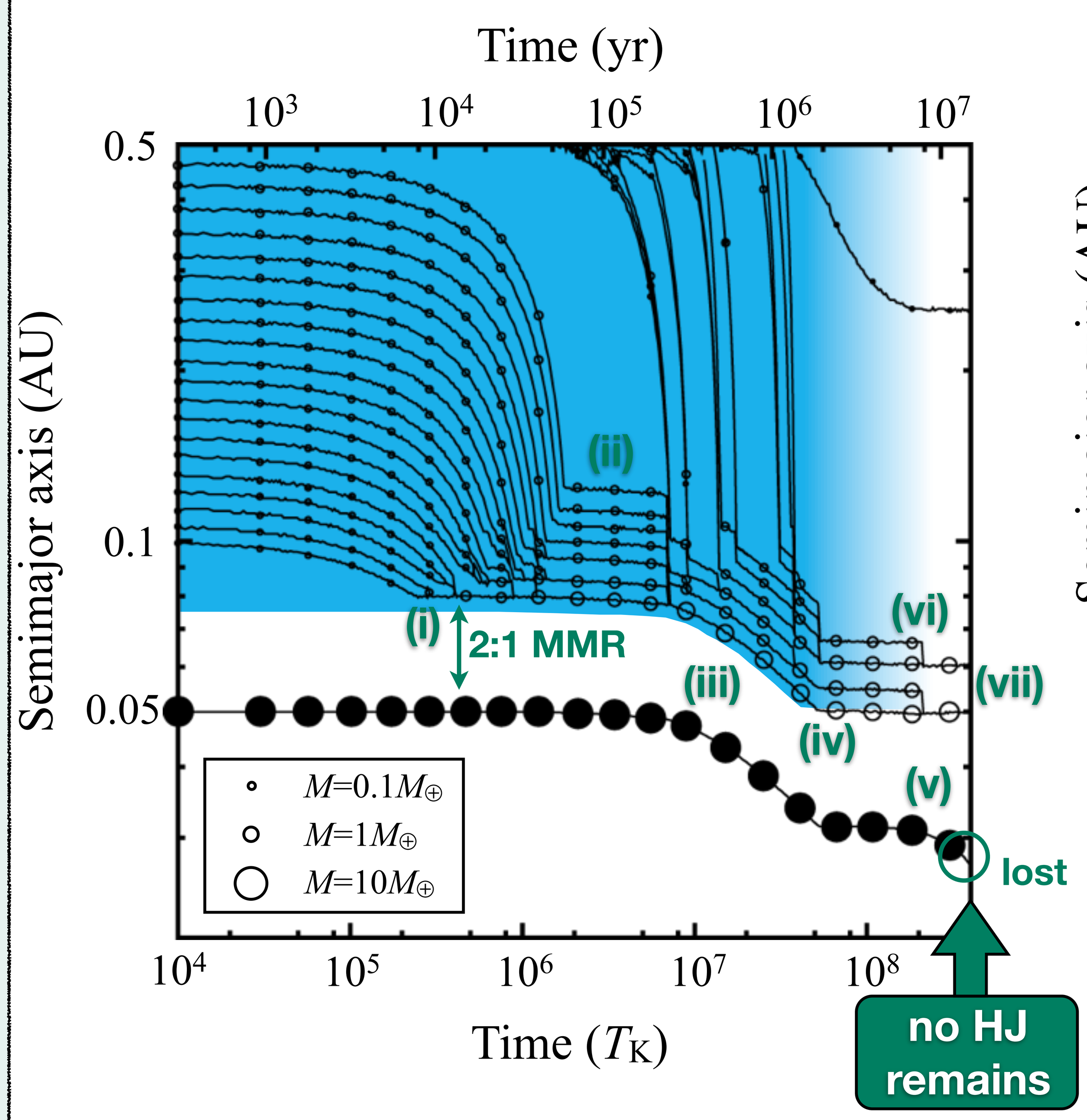
The simulation domain of N-body calculation is set between 0.02-0.5 AU and the gravity between all the bodies are calculated. For the initial solid disk, the solid surface density is assumes as

$$\Sigma_d = 10 f_d \left(\frac{r}{1\ \mathrm{AU}}\right)^{-3/2}\ \mathrm{g\ cm^{-2}},$$

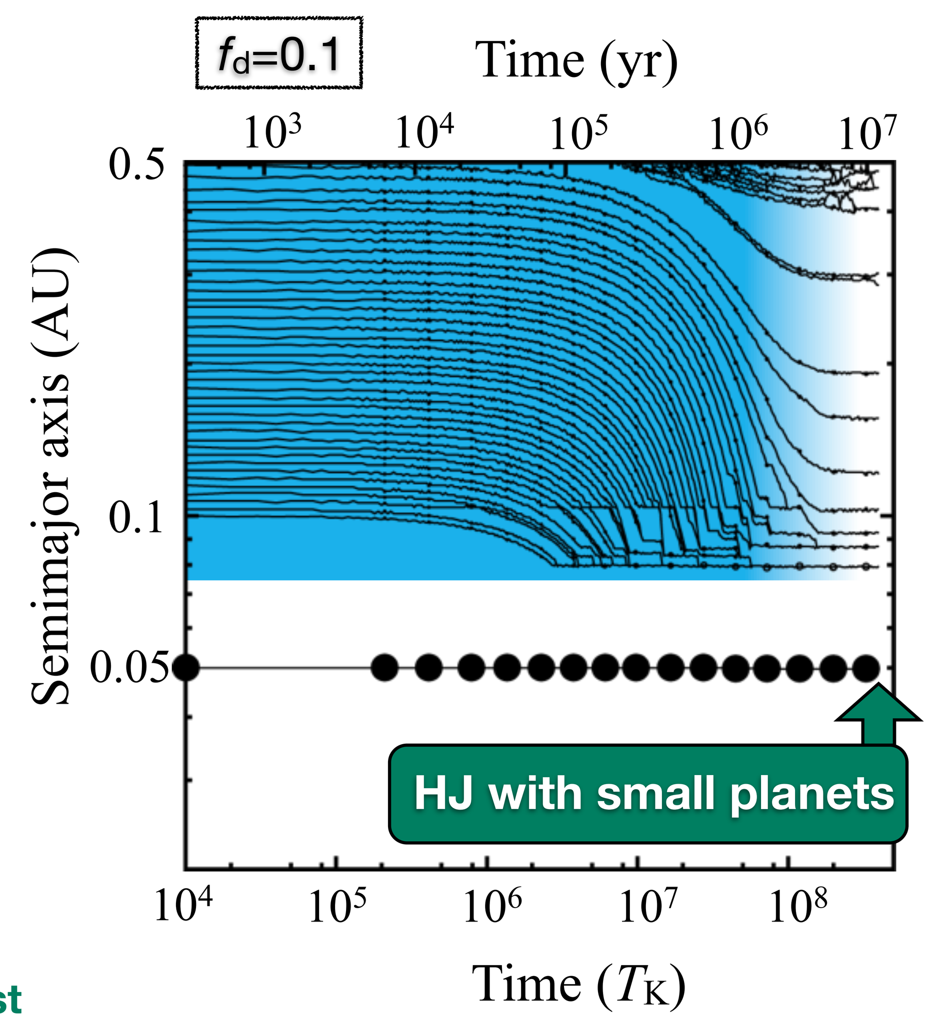
where f_d is a scaling factor. According to this density distribution, planetary embryos are placed with the isolation mass. A HJ with Jovian mass is placed at 0.05 AU. We consider the effects of the gas disk, such as type I migration; thus protoplanets migrate in to the simulation domain from beyond 0.5 AU. In order to take into account the mass inflow into the simulation domain, we also simulate the growth and migration of protoplanets beyond 0.5 AU by semianalytical code. When protoplanets reach the boundary (a=0.5AU), the bodies are added to the N-body code. We adopt the MMSN model for the gas surface density, which dissipates with the depletion timescale of 10^6 yr = 3×10^7 T_K. The HJ can open up a gap near its orbit. We use an analytical description for the computation of the gap profile (Crida et al. 2006) assuming relatively high turbulent viscosity (α=0.01). In this case, the location of the gap edge is closer to the HJ than that of 2:1 MMR with the HJ.

3. RESULTS

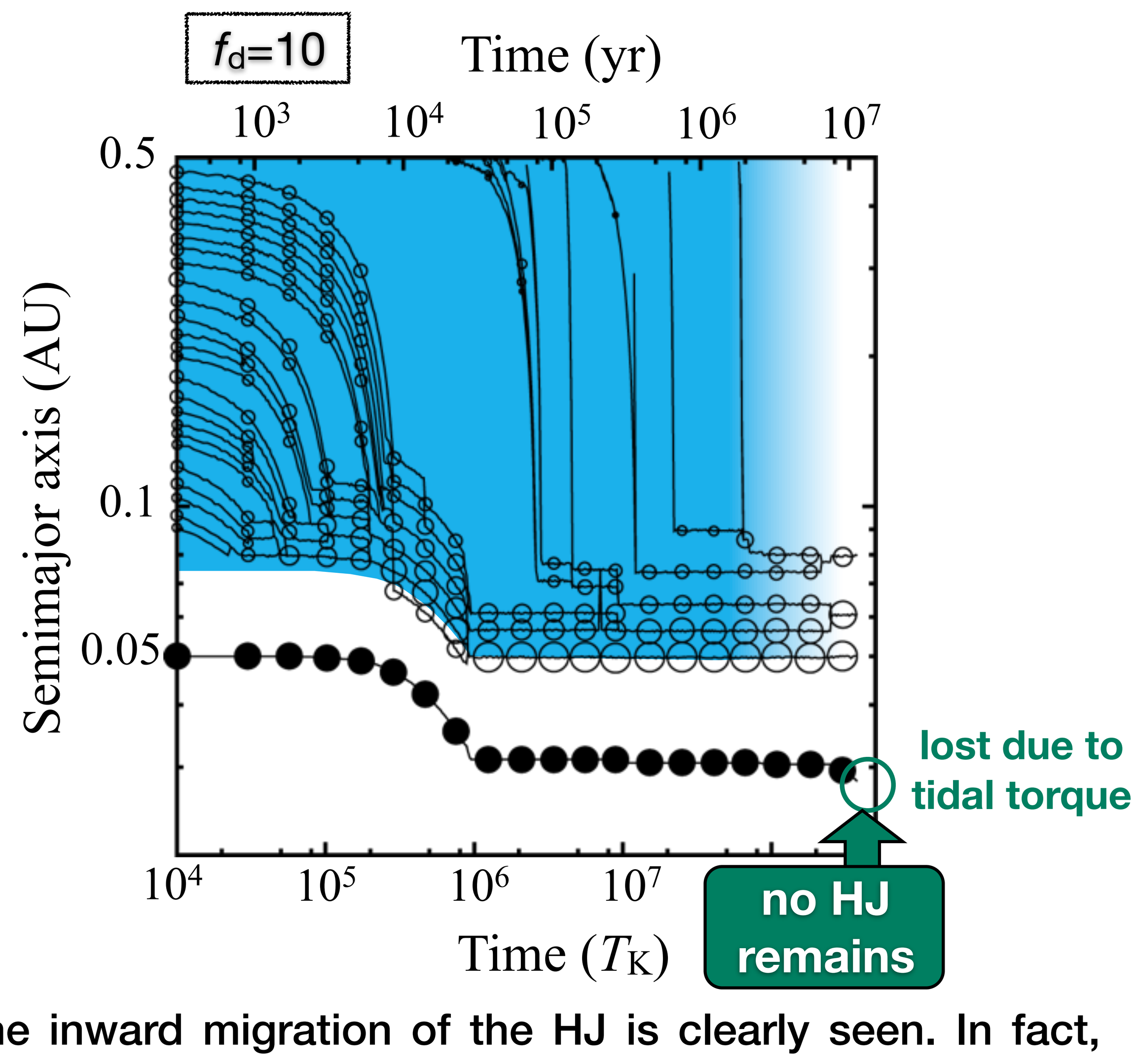
Typical result (f_d=1)



Several features are seen in our results as follows. (i) Embryos undergo inward type I migration, and the innermost planet ceases its migration when it is captured into the 2:1 MMR with the HJ. (ii) After other embryos exhibit inward migration, several planets relax to a quasi-steady state captured in MMRs, which is called a resonant chain. (iii) The HJ, which is free of the influence of the gas drag, migrate inward by being pushed in by the resonant chain, which we call "crowding-out effect." (iv) When the innermost planet reaches the disk inner edge, the planet experiences the positive torque due to the positive density gradient of the disk (e.g., Masset et al. 2006). As a result, the migration is halted. (v) The disk gas is depleted on the timescale of 10^6yr=$3\times10^7 T_K$. Then, the HJ migrates inward due to the effect of the tidal torque and is lost to collision with the star. (vi) Several planets exhibit orbit crossing and giant impact events are observed, which results in losses of commensurate relationships. (vii) Three planets with masses of ~$2.3M_\oplus$ remain at the end of simulation.



The inward migration of the HJ owing to the crowding-out effect is not seen in the result of decreased solid density. The angular momentum loss is not large enough because of the small masses of the planets in the resonant chain.



The inward migration of the HJ is clearly seen. In fact, the timescale of inward migration of the HJ is shortened.

4. DISCUSSION

Our results give several possible explanations for the origin of the lack of companion planets in HJ systems.

1. Loss of HJs by crowding-out effect

(see the cases of f_d=1 and 10)

When the chain of resonant planets interacts with the HJ through resonant interaction, the HJ can be pushed inward, leading to a collision with the central star. Therefore, the HJ is never observed, whereas other low-mass planets remain around 0.1AU.

2. Formation of small planets outside HJs

(see the case of f_d=0.1)

The other explanation is that the HJ and companion planets may coexist, but their masses and/or sizes are below the detection threshold of the current survey. As displayed in the case of f_d=0.1, the HJ can remain in the vicinity of the central star. In this case, large planets do not form; these planets may be below the detection limit.