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Origin of close-in super-Earths: In-situ formation in an evolving disk due to disk winds

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Abstract

Observations of extrasolar planets have revealed a number of close-in super-Earths; however, their origin is still a matter of debate. We investigate the formation of close-in super-Earths in a protoplanetary disk that viscously evolves under the effects of magnetically driven disk winds by performing *N*-body simulations. We find that the type I migration is significantly suppressed because the gas surface density is decreased and has a flatter profile in the close-in region due to disk winds. When the type I migration is significantly suppressed, planets in a chain of mean-motion resonances undergo late orbital instability during the gas depletion, leading to a non-resonant configuration. In this case, observed distributions of close-in super-Earths (e.g., period ratio) can be reproduced by results of our simulations.

1. Introduction

Formation models of close-in super-Earths can be divided into two groups; namely, in-situ formation models and migration models. According to a recent study of in-situ formation of close-in super-Earths, planets grow and migrate very rapidly in a power-law disk based on the minimum mass solar nebula [1]. As a result, super-Earths form in a highly compact configuration near the disk inner edge, which is inconsistent with observed distributions.

Recent magnetohydrodynamic (MHD) simulations revealed the existence of magnetically driven disk winds [2, 3]. The global disk evolution including effects of disk winds was also investigated, which showed that disk profiles in the close-in region can be altered from a power-law distribution [4].

In this study, we perform *N*-body simulations of super-Earth formation from planetary embryos in a protoplanetary disk evolving with disk winds. Our main goal is to reproduce observed properties of close-in super-Earths by results of our *N*-body simulations.

2. Model

For evolution of disk surface density, we numerically solve the diffusion equation that includes effects of disk winds based on MHD simulations (the same as used by previous study [4]). As there exists uncertainties in the disk evolution model, we use several model parameters (e.g., turbulent viscosity). We find that when the turbulent viscosity is high ($\alpha \simeq 8\times10^{-3}$), the disk surface density obtains a flat profile in the close-in region (see the red line in Figure 1).

We start *N*-body simulations with planetary embryos of 0.2 Earth masses that are distributed in a ring-like region between 0.1 and 2 au from the central star. Orbital evolution is calculated by a fourth-order Hermite scheme with a hierarchical individual time step. For the formulae of type I migration, we use those described in a paper that takes into account the saturation of corotation torque [5].

3. Results

Figure 1 shows snapshots of the system for typical outcome of *N*-body simulations. Growth of planets proceeds from the inner region, and the mass of grown planets is larger than 1 Earth mass at $t > 0.1$ Myr. These planets should undergo rapid inward migration in the power-law disk model based on the minimum mass solar nebula; however the type I migration is significantly suppressed in a flat disk profile with effective desaturation of positive corotation torque. Most planets are in relatively close mean-motion resonances before the gas depletion, which are disrupted by orbital crossings during the gas dissipation phase ($t > 1$ Myr). In the final state, several close-in super-Earths form in a non-resonant configuration.

We perform a series of *N*-body simulations to statistically compare our results with observed distributions of close-in super-Earths. We find that the observed period-ratio distribution can be reproduced when planets do not undergo significant migration in a gas disk and resonant relationships are disrupted by orbital crossings during the disk dissipation phase. We also find that results of our *N*-body simulations are basically consistent with other observed characteristics (see also [6] for more details).

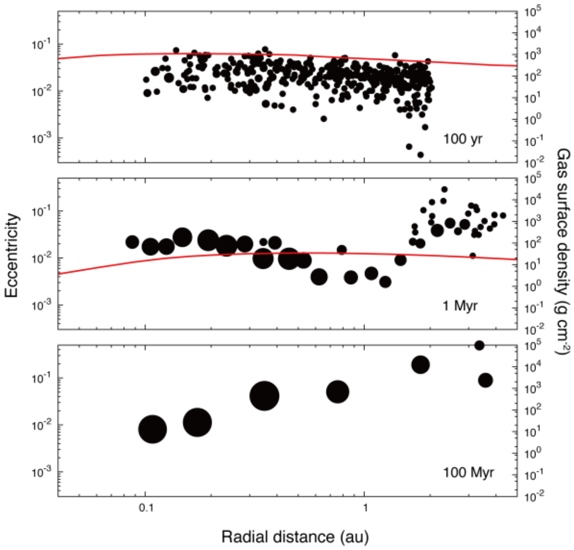

Figure 1: Snapshots of the system for our typical simulation. The filled circles represents the size of particles. The red lines indicate the gas surface density (right axis).

4. Summary and Conclusions

When the disk profile is altered due to the effect of disk winds, type I migration of super-Earth cores can be significantly suppressed. Slowly migrating planets are captured in mean-motion resonances. Such planets undergo late orbital instability during the gas dissipation phase, leading to a non-resonant configuration. In this case, observed distributions of close-in super-Earths (e.g., period ratio) can be reproduced.

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