Formation of Close-in Super-Earths by Giant Impacts: Effects of Initial Eccentricities and Inclinations of Protoplanets

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Nowadays, dozens super-Earths, which are composed rock or ice, are already found in orbits that are close to their stars (e.g., [1]). Recent observations have reveled the orbital eccentricity (e) and orbital inclination (i) distributions of super-Earths [2,3]. We considered how the eccentricities and inclinations of close-in super-Earths are determined in the giant impact stage. These evolve through gravitational scattering and collisions between protoplanets in gas-free environments. The eccentricities are increased by scattering between protoplanets [4], and they are damped by collisions [5]. The collisions tend to occur at the point where their orbits initially crossing since the small scattering cross section of protoplanets in the close-in region. The orbital crossing initially occurs around the apocenter of the inner protoplanet and the pericenter of the outer planet. As a result, the velocity of merged body is about equal to the Kepler velocity.

We studied the effects of the initial e and i of protoplanets on the final orbits of planets formed by giant impacts [6]. We performed N-body simulations of the protoplanet accretion over 500 times. Numerical computations were carried out on the PC cluster at the Center for Computational Astrophysics, NAOJ.

We found that the final eccentricities do not depend on initial eccentricities, when orbits of protoplanets are initially not crossed. While the eccentricities gradually increase with each collision if initial e is small, they gradually decrease when initial e is large. The final planets become similar due to these relaxations.

On the other hand, the initial inclinations are not relaxed. When the initial i is small, the velocity dispersions normal to the disk midplane keep small through scattering, and the final planets have small i. If the initial i is large, collisions do not occur immediately after orbital crossing, since they can collide only in parts of their orbits. Protoplanets experience more scattering until a collision, which make i larger. This is why the merged protoplanets have larger i. And, final inclinations of planets depend on initial inclinations. The eccentricities In large i cases are larger those in small i cases due to more scattering. We found that the inclinations of observed planets are consistent with our results, if protoplanets initially have $\sim 10^{-3}$–10^{-2} rad inclinations (Figure 1, [6]).

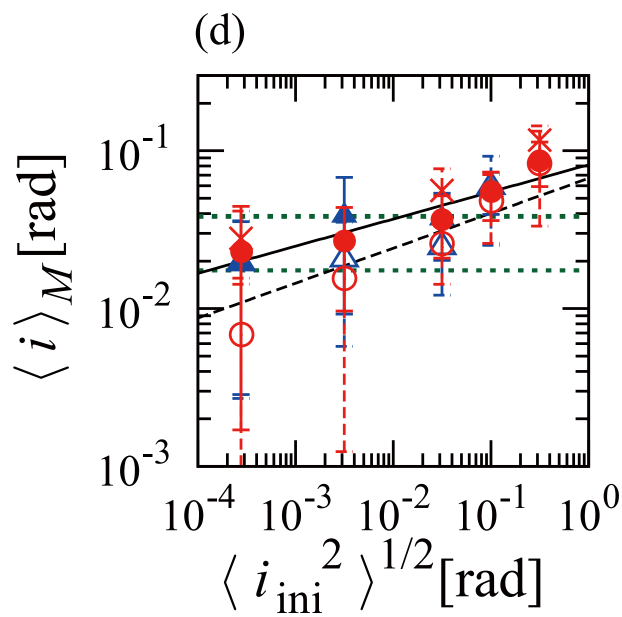

Figure 1: This figure is from the panel (d) of Figure 9 in [6]. The mass-weighted inclination ($\langle i \rangle_M$) is shown as a function of the initial inclination dispersion of protoplanets ($\langle i^2_{\rm ini} \rangle^{1/2}$). The error bars indicate the standard deviation. The filled symbols are the results of models that initial number of protoplanets is $N_{\rm ini}$ = 16 (models N16), the open symbols are those of models N8, and crosses are those of models N32. The initial eccentricity dispersions are different between red circles and blue triangles. The solid and dashed lines are the fits by the least-squares-fit method for models. The dotted lines shows the mode of the mutual inclination [2,3].

References

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