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The formation of close-in planets through a coupling effect of planet scattering and tidal circularization

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We have investigated the formation of close-in planets by a combination effect of mutual scattering, Kozai mechanism, and tidal circularization.

Many short-period Jovian or Neptunian planets are discovered outside of the solar system. These planets would have been formed at large distances beyond the ice line and migrated to shorter-period orbits. A promising mechanism for the orbital migration is type-II migration. However, several close-in planets have relatively large eccentricities but are not accompanied by nearby secondary large planets. For example, a close-in planet HD17156 has the eccentricity of $\sim$0.67 and the inclination with respect to the equator of the host star of 62 ± 25 degree. It may be difficult for type-II migration alone to generate such eccentricity and inclination.

The large eccentricities and inclinations can be produced by scatterings by other giant planets. We have carried out orbital integrations of three planets with Jupiter-mass, including the effect of tidal circularization. We have found that close-in planets are often formed with moderate eccentricities and inclinations. This is because that Kozai mechanism caused by outer planets repeatedly excites the eccentricity of the innermost planet during the three-planet orbital crossing. The eccentricity is often increased to values enough for tidal circularization to transform the inner planet to a close-in planet. Close-in planets are formed after the planet scatterings in about 30% of our runs. Formed close-in planets also remain a broad range of orbital inclinations including retrograde orbits. The process of planet scattering and tidal circularization can give a non-negligible contribution for formation of close-in planets, in particular for the close-in planets with moderate eccentricities and inclinations.