The effect of the three-dimensional gas flow around an embedded planet on pebble accretion

*Ayumu Kuwahara[1], Hiroyuki Kurokawa[2]

1. Tokyo Institute of Technology, 2. Earth-Life Science Institute

Pebble accretion is a new model of planet formation, which may overcome several problems remaining in conventional planetesimal accretion theory. Accreting mm—cm-sized particles, called pebbles, onto the proto-cores can form the massive cores faster than accreting the planetesimals. In addition to the formation of the Jovian cores in a realistic timescale, pebble accretion scenario can explain the formation of various types of planets—for instance, close-in super Earths, water-rich planets, and the size distribution of terrestrial planets in the solar system. The key point of this scenario is that the pebbles experience not only the gravitational interaction with the proto-cores but also gas drag. The hydrodynamic effect is important when we consider the planet formation via pebble accretion.

Previous works have found the three-dimensional flow field around an embedded planet. Gas from the protoplanetary disk enters the Bondi or Hill sphere of the planet at high latitude and exits through the mid-plane region in the isothermal condition (Kuwahara et al. 2019). This recycling mechanism may have both positive and negative effect on the accretion of solid materials. When the particles are moving in the region at high latitude of the planet, the accretion may be promoted by the inflow of gas. On the other hand, if the particles are in the mid-plane region, the accretion of the particles can be suppressed by the outflow barrier. Though some studies considered the accretion of dust particles in the realistic flow field (Ormel 2013; Popovas et al. 2018ab), the effect on the accretion efficiency is not fully understood. This study aims to understand the hydrodynamic effect and to obtain the accretion efficiency of particles for the range of planetary masses and particle sizes.

In this study, using the numerical data obtained from three-dimensional hydrodynamical simulations, we numerically integrated the equation of motion of pebbles including the gravitational interactions and gas drag under the influence of the flow field in three dimensions. We also performed the similar calculations on the Keplerian shear flow field without the effect of planet gravity on the flow, then investigated how the description of the pebble accretion changed on the flow pattern, pebble size, and dimensionless planetary mass, $m=R_{\mathrm{Bondi}}/H$, where R_{Bondi} and H are the Bondi radius of the planet and disk scale height, respectively.

In the flow field, we found that the description of pebble accretion differs from that of in the Keplerian shear flow. Pebbles at high altitude tend to descend toward the planet because of the downward stream of gas. The accretion rate of pebbles became smaller than in the Keplerian shear flow. In spite of the pebbles descend toward the planet, the accretion of pebbles can be suppressed because of the effect of the flow field. Since the gas flows rapidly in the vicinity of the planet, the gas flow field deflects the trajectories of the pebble in the vicinity of the planet and reduces its accretion rate. The flow field has the stronger effect on the smaller pebbles. Based on these results, we will discuss the implications for planet formation via pebble accretion.

References:

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